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AN EVALUATION OF GROUND COLLISION AVOIDANCE SYSTEM ALGORITHM

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Final Report

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NOTICE

This technical report has been reviewed and is approved for publication.

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Controlled flight into terrain (CFIT) accidents, which constitute the second largest category of tactical Air Force Class A mishaps, could be greatly reduced by installing forward-looking Terrain-Following Radar (TFR) Systems. In an effort to design a less costly solution to this problem, a software-oriented generic Ground Collision Avoidance System (GCAS) with application to more complex tactical missions was developed. A simulation study of the system evaluated the adequacy of the algorithm in a variety of tactical scenarios. Results indicate GCAS is a viable system for partial solution of CFIT. Although some modifications to the system are necessary prior to implementation, the concept of terrain estimation may give GCAS a capability unmatched by any similar systems.

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INTRODUCTION

Although the Air Force accident rate in recent years has been at an all time low, many feel that an even lower rate could be achieved by reducing the number of controlled flight into terrain (CFIT) accidents, which constitute the second largest category of tactical Air Force (TAF) Class A mishaps. Air Force investigations concluded that between 1975 and 1981, there were 56 fighter and attack aircraft involved in CFIT accident mishaps. The United States Navy has attributed the loss of 317 aircraft to CFIT accidents between 1970 and 1984. Of course, the occurrence of CFIT could be greatly reduced in the tactical fleet by installing forward-looking Terrain-Following Radar (TFR) systems, but such a solution would be prohibitively expensive and possibly unnecessary. Since a significant percentage of accidents occur during low level missions while flying over sloping terrain that is not particularly severe, it has been proposed that a less costly solution to the problem may be a system based on less complicated sensors, such as a radar altimeter system, that would cover a part of the CFIT envelope instead of all of it.

Such an approach has been highly successful on commercial airliners and some wide body military transports which are equipped with a Ground Proximity Warning System (GPWS). The CFIT accidents for commercial aircraft have in fact dropped to virtually zero since 1976, when GPWS use was mandated by the Federal Aviation Administration. However, the much more complex nature of tactical application cannot be accomodated by the system currently available in commercial and wide-body aircraft. In an effort to develop a Ground Collision Avoidance System (GCAS) which may have application to the much more complex tactical mission, the Air Force has contracted with Cubic Corporation to develop a generic GCAS system that is software oriented with a minimum of complex sensors required. Such a system was developed and has been flight tested on a limited basis. Due to safety considerations and in order to assess GCAS in a wider variety of tactical situations, the CSDF was requested to conduct a simulation study of the generic GCAS. The overall objective of the simulation study was to evaluate GCAS in a variety of tactical scenarios. More specifically, the purpose of the simulation was to provide the following data to the GCAS program office:

a. Evaluate the adequacy of the algorithm to provide a warning in sufficient time for a pilot to recover in a variety of CFIT Scenarios.

b. Evaluate the impact and incidence of nuisance warnings generated by the algorithm.

c. Provide data to further refine and flight test the algorithm.

d. Assess pilot reaction to GCAS.

e. Provide normative data on pilot response time to GCAS warnings.

SECTION II

STUDY PROCEDURE

1. APPARATUS

The apparatus for conducting this experiment was the Crew Station Design Facility, which has the capability to dynamically simulate a complete flight regime under a variety of controlled conditions. The facility consists of six basic components:

a. Three crew station shells - A-10, F-16, and C-135/C-18.

b. A digital computer complex consisting of five Gould Model 77/80SEL computers, one Gould Model 8780 SEL computer and a Digital Equipment Corporation Model PDP 11/34. All cockpits are interfaced through a Singer Advanced Simulator Technology (AST) interface.

c. A visual simulation complex consisting of a Singer Link NVS Night Caligraphic Visual System and Singer Dual SMK-23 Camera Model Visual System.

d. Radar simulator equipment.

e. Monitors and Recording equipment.

f. Computer graphics complex.

The CSDF F-16 Flight Simulator was used as the test vehicle for this study. An out-of-the-cockpit visual scene was provided using a closed-circuit TV system from a modified Link SMK-23 moving terrain model. The visual system consisted of a high resolution, low light level TV camera and a Farrand optical probe, which transferred the mountainous terrain images to a Conrac 1000 line, black and white TV monitor. The scene was transmitted through a beam splitter and parabolic mirror with a focal length of 54 inches. This provided approximately a 48-degree-forward field of view (FOV) to the pilot with the image collimated to appear at infinity. The system provided simulated aircraft visual parameters of 360 degrees continuous heading, 360 degrees of continuous roll, plus or minus 120 degrees of pitch, and 50 to 4000 feet altitude. All aircraft aerodynamics and aircraft systems were computed on the SEL computer complex. The Voice Warning System was used to transmit digitized warnings (pull-up, pull-up) to the pilot for each GCAS event. Objective data parameters collected on each mission were taken from the SEL computers and recorded on magnetic tape for subsequent review and analysis. Figures 1 and 2 provide an illustration and diagram of the apparatus.

The experimenter's console provides controls and displays for mission setup, simulator operation, data collection equipment, and various control and display mechanization options. For this evaluation there were three options available to the experimenter to change simulator position and attitude. One option allowed the console operator to move the simulator forward 3000 feet in the flight plan to simulate a late pop-up on weapon delivery runs. When this occurs in the real world, the pilot has no difficulty finding his pull-up point, pulls up too close to the target and ends up making his dive-bomb pass at a steeper than normal delivery angle. This feature was used on missions 14 and 15 (auto pull-up missions 24 and 25) to complicate the delivery task.

Another option allowed him to decrease simulator altitude in increments of 1000 feet. This was used most often on mission 16 (auto 26) to simulate entry into dynamic maneuvers at a lower than expected altitude. This led to unexpected GCAS warnings in attitude and flight path conditions approaching the limits of system operation and in some cases, disorientation.

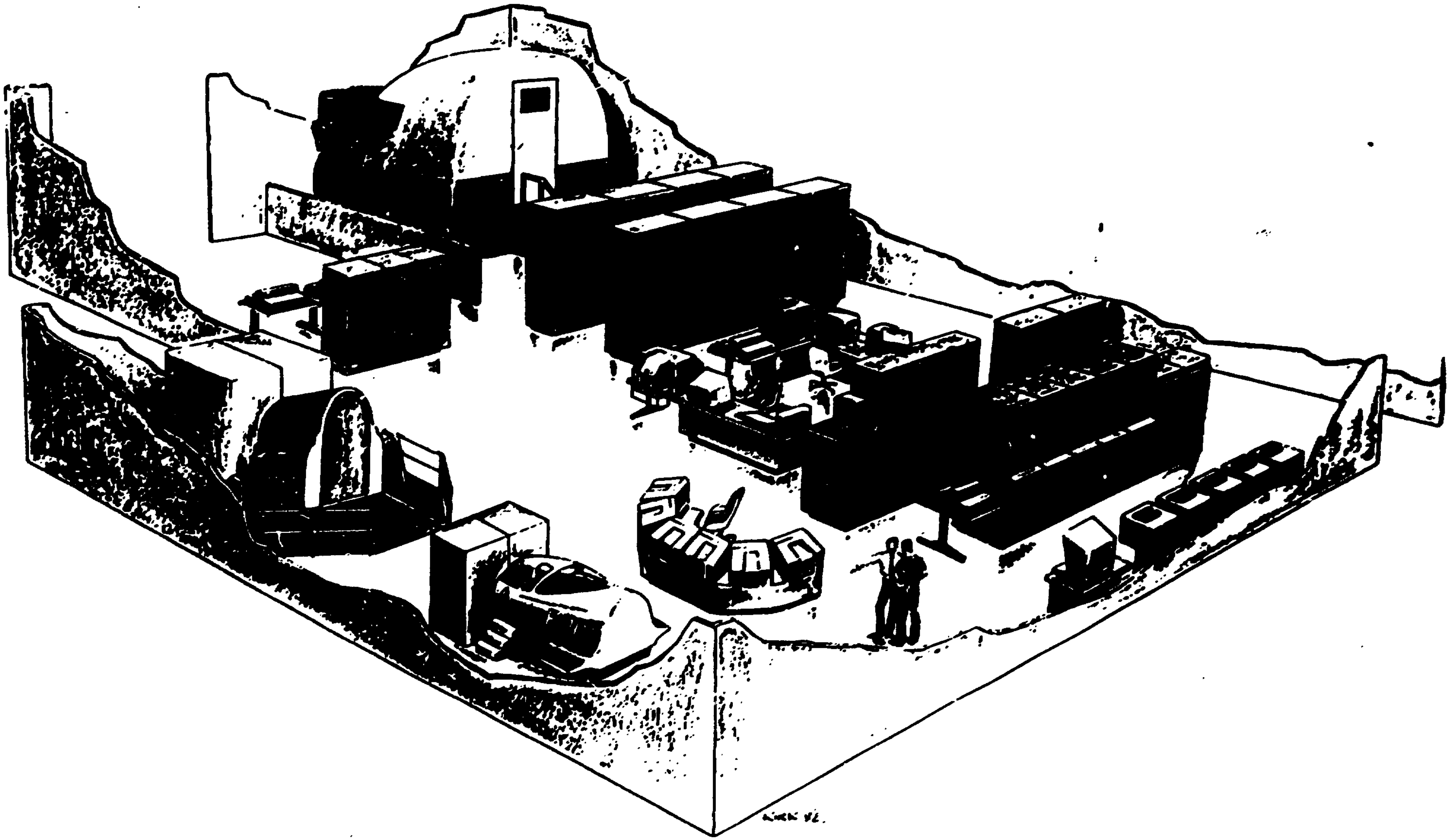

Figure 1. Crew Station Design Facility

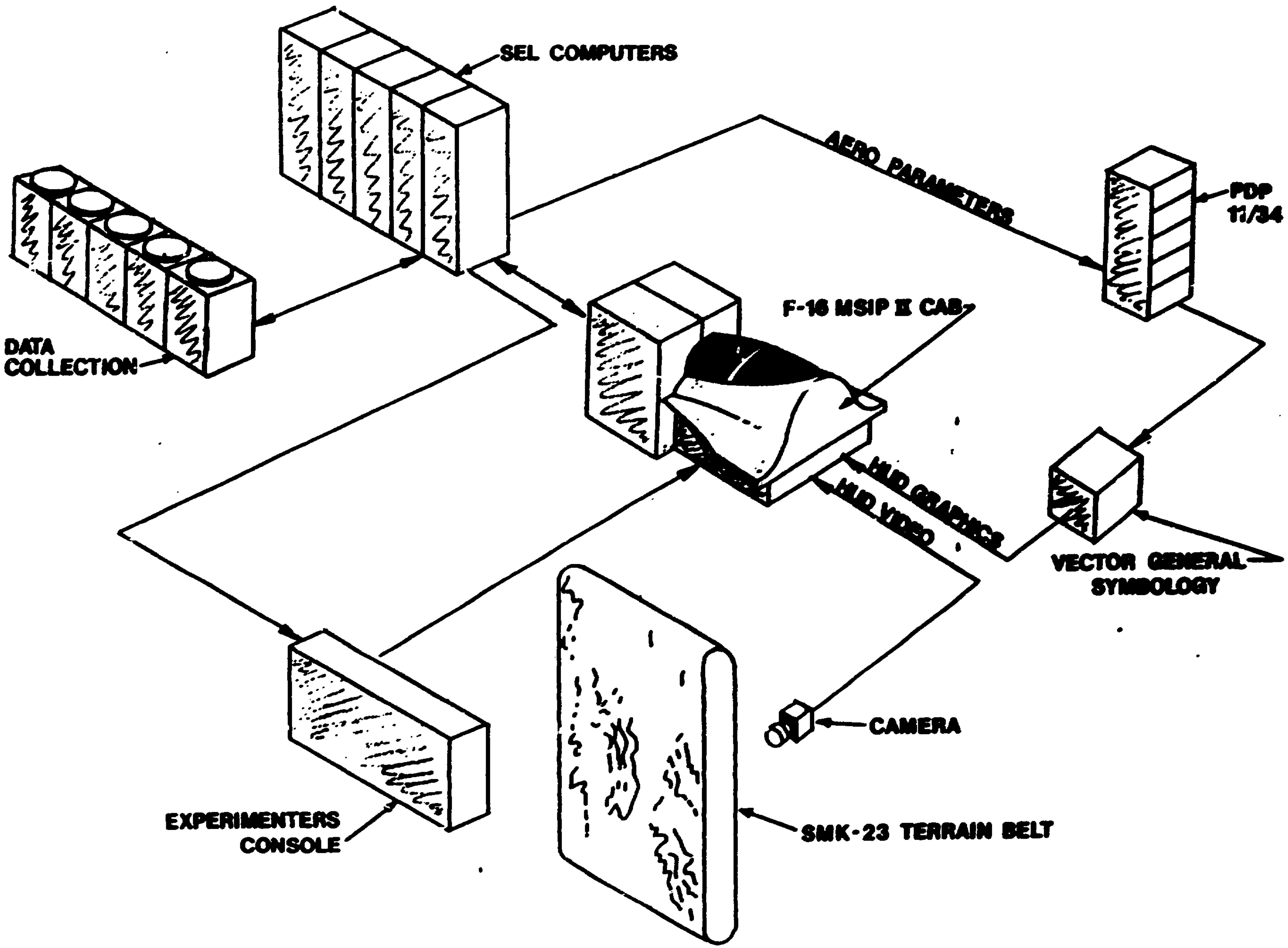

Figure 2. Functional Diagram of Crew Station Design Facility

The final option dealing with simulator control was the mechanization of a joy stick on the console to operate in series with the pilot's control stick. With this capability, the experimenter could change aircraft pitch and roll attitudes during periods of pilot distraction to simulate entry into unusual (or unexpected) attitudes. This control feature was used effectively during low level navigation and high "G" turning flight when pilots were instructed to read authentication and alphanumeric cards.

2. SUBJECTS

A total of 10 subject pilots participated in the study. Eight of the pilots were operational pilots from the Tactical Air Command (TAC), and two were pilots from Wright-Patterson AFB with previous tactical experience in the low level environment. The pilots had varying amounts of experience in the F-16 as indicated in Table 1. They arrived over a 2-1/2 week period with an average of four pilots participating each week (two subjects over a 2-1/2 day period).

3. PROCEDURE

When the pilots arrived to participate in the study, they filled out a personal data questionnaire (see Appendix) and were given a general overall briefing on the program. A detailed briefing on the GCAS algorithm was also presented along with "ground school" on the F-16 simulator. The pilots flew a training mission in addition to the briefings to conclude the inital half-day period. In the ensuing day and a half, the pilots flew 12 missions in which various data described earlier were collected. In the last half-day block, each pilot was debriefed and filled out a questionnaire. A detailed schedule of events for each pair of pilots is in the Appendix.

TABLE 1

PILOT'S FLYING TIME

SUBJECT NUMBER	TOTAL FLYING TIME (HRS)	TOTAL F-16 TIME (HRS)
1	350	150
2	400	110
3	1500	1250
4	1700	350
5	600	350
6	300	200
7	1780	780
8	1700	640
9	2000	600
10	1170	0
	M= 1155	443

Pilot briefings prior to each data collection flight covered the overall mission scenario, specific objectives of the mission, altitudes, speeds, times, etc. Pilots were also provided with a mission setup checklist and a strip map of the route of flight when appropriate. Mission briefing outlines are provided in the Appendix. Following the briefing, each pilot was taken to the simulator to fly the test mission.

When the pilot had completed cockpit setup actions, previewed the mission and indicated that he was ready to start the run, the simulator and data recording equipment were activated and the mission started. Voice communications were held to a minimum during each evaluation run and limited to responding to the pilots' questions, or as was the case with missions 11 and 15 (auto 21 and 25), recording his assessment of the validity of GCAS warnings, since these were the only missions where he was in a position to assess validity of the warning as valid, invalid (expected), or invalid (unexpected).

Following each simulated mission, a short debriefing session provided an opportunity for the experimenter and evaluation pilot to discuss simulator and GCAS operation. During these sessions, the experimenter recorded pilot comments on GCAS operation as it applied to the mission just flown. The questionnaire with pilot comments can be found in the Appendix.

4. DATA COLLECTION

Table 2 shows the flight parameters and performance measures that were collected during all test missions. These parameters were to reconstruct the flights for more definitive evaluation. The critical flight parameters were plotted as time histories for each maneuver causing a warning. The data were plotted from a period of 5 seconds prior to the warning to the minimum recovery altitude above ground. These data plots were used to reconstruct each GCAS event for data analysis and assessment of pilot performance.

5. EXPERIMENTAL DESIGN

The experimental design was a treatment x treatment x subjects (2x2x10) or ABS design as described in Lindquist's Design and Analysis of Experiments in Psychology and Education (Ref 1). The treatment variables were (1) type of recovery (manual or automatic) and (2) type of mission (six representative tactical missions). The manual pull-up data were used to assess pilot performance and the automatic pull-up data were to analyze the algorithm (i.e., provide consistent response without

TABLE 2 FLIGHT PARAMETERS

FLIGHT PARAMETERS	UNIT OF MEASUREMENT	RANGE
Pitch Attitude	degrees	±90
Roll Attitude	degrees	±180
"G" load	"G"	-3 tc +10
Flight Path Angle	degrees	±90
Pitch Rate	degrees/sec	±45
Absolute Altitude	feet	0-1000
Barometric Altitude	feet	0-6000
Heading	degrees	0-360
Roll Rate	degrees/sec	±75
Yaw	degrees	±45
Terrain Angle	degrees	±60
GCAS triggered Pull-up time	sec	Discrete
Altitude at GCAS alarm	feet	Discrete
Altitude clearance at pull-up instance	feet	Discrete
Engine RPM	%RPM	Idle-95
Groundspeed	knots	0-600
True Airspeed	knots	0-600
Angle of Attack	degrees	
Stick Force	lbs	Discrete
Time from alarm to change in stick force (response time)	clock	Seconds

variations in response time).

6. MISSIONS

Six missions were designed to test the algorithm. Overall objectives in designing the profiles were to subject the pilot to a variety of conditions representative of those encountered in tactical fighter operations with specific emphasis on the kinds of situations reported in CFIT incidents. A complete description of each mission follows:

1. Low Level Navigation - Mission 11: This mission was flown at 300 to 500 feet above the terrain. Some segments of the route were level terrain, between ridges, simulating typical terrain masking operations while other segments required ridge crossings and flight over rough terrain (Figures 3 and 4).

2. Low Speed Maneuvering IMC - Mission 12: This mission was designed to simulate radar vectors for approach or low level, low speed, navigation where the controller or the pilot selected a maneuvering altitude below minimum safe altitude and slightly below the level of ridges along the route of flight. Flown at 1500 feet MSL (altitude below ridgetops), 250KCAS and in instrument meteorlogical conditions, this mission looked at the algorithm in a nearly level flight, wings level condition where the pilot had no external visual cues from outside terrain.

3. Hard Turns at Low Altitude - Mission 13: This mission was flown over level terrain at 480KCAS in a figure-eight pattern between two steerpoints. At each steerpoint passage, the pilot initiated a 5 'G' turn of about 210 degrees to simulate defensive maneuvering at low level 300 to 500 feet). During the turns, pilots were asked to read a series

of numbers and letters from a card located on the canopy over his head to simulate checking 6 o'clock for other aircraft. Adjustments to aircraft attitude were made by the experimenter during the turns on this mission to further complicate the recovery task (Figure 5).

4. Range Mission - Mission 14: This mission consisted of a series of three runs on the same target from different approach headings simulating a low level range familiarization flight. The profiles were flown at 300 to 500 feet and 480 KCAS on the low level navigation segments. Delivery maneuvers consisted of a 30-degree straight ahead pop at 20 seconds prior to the target, a climb to 4000 feet MSL and a roll to inverted flight for the pull down to a 30-degree dive. Bomb release was briefed to be completed at 2500 feet MSL. To complicate the delivery, the experimenter could move the aircraft (simulation) forward 3000 feet during the a steeper then desired, or expected, dive angle that had to be used to bring the target into view (Figures 6 and 7).

5. Low Level Navigation/Pop-Up Deliveries - Mission 15: The low level portions of this mission were essentially the same as described in Mission 11 above except that three targets were selected along the route of flight for pop-up weapons delivery maneuvers. Like the range mission above, the pop was initiated 20 seconds prior to the target for a 30 degree delivery. Again, the experimenter could advance the simulator in the pop so that the aircraft would be outside delivery parameters in the pull-down (Figures 8 and 9).

6. IMC Maneuvering - Mission 16: This mission flown in IMC was made up of a series of aerobatic maneuvers. These maneuvers required the pilot to recover from relatively extreme pitch and bank attitudes such as might be encountered in unusual attitude or spatial disorientation incidents (Figure 10).

On some of the manuevers such as the loop, split s, and Cuban 8, the experimenter adjusted simulator altitude 3000-4000 feet to cause early GCAS alarms.

Figure 3. Mission 11

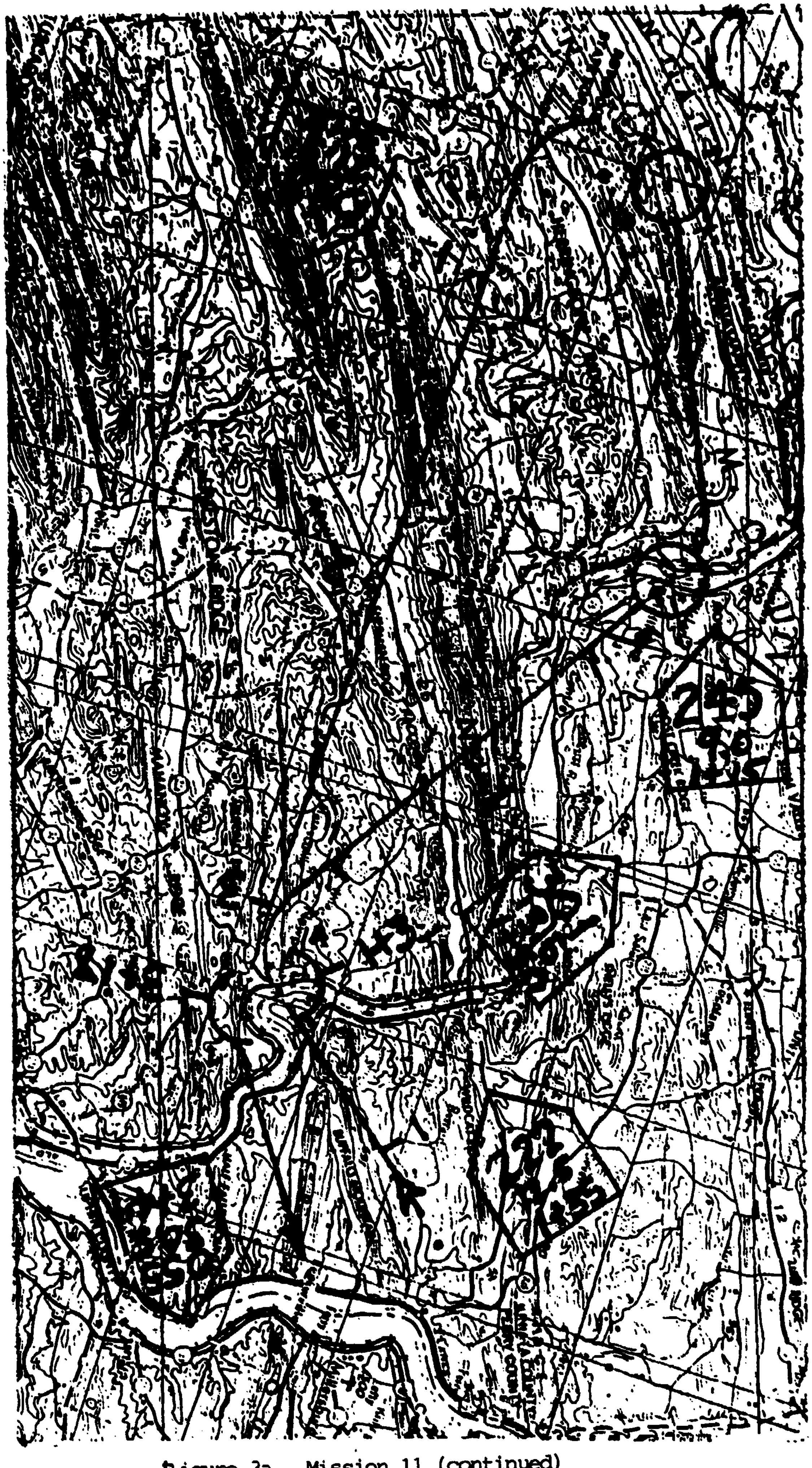

Figure 3a. Mission 11 (continued)

Figure 3b. Mission 11 (continued)

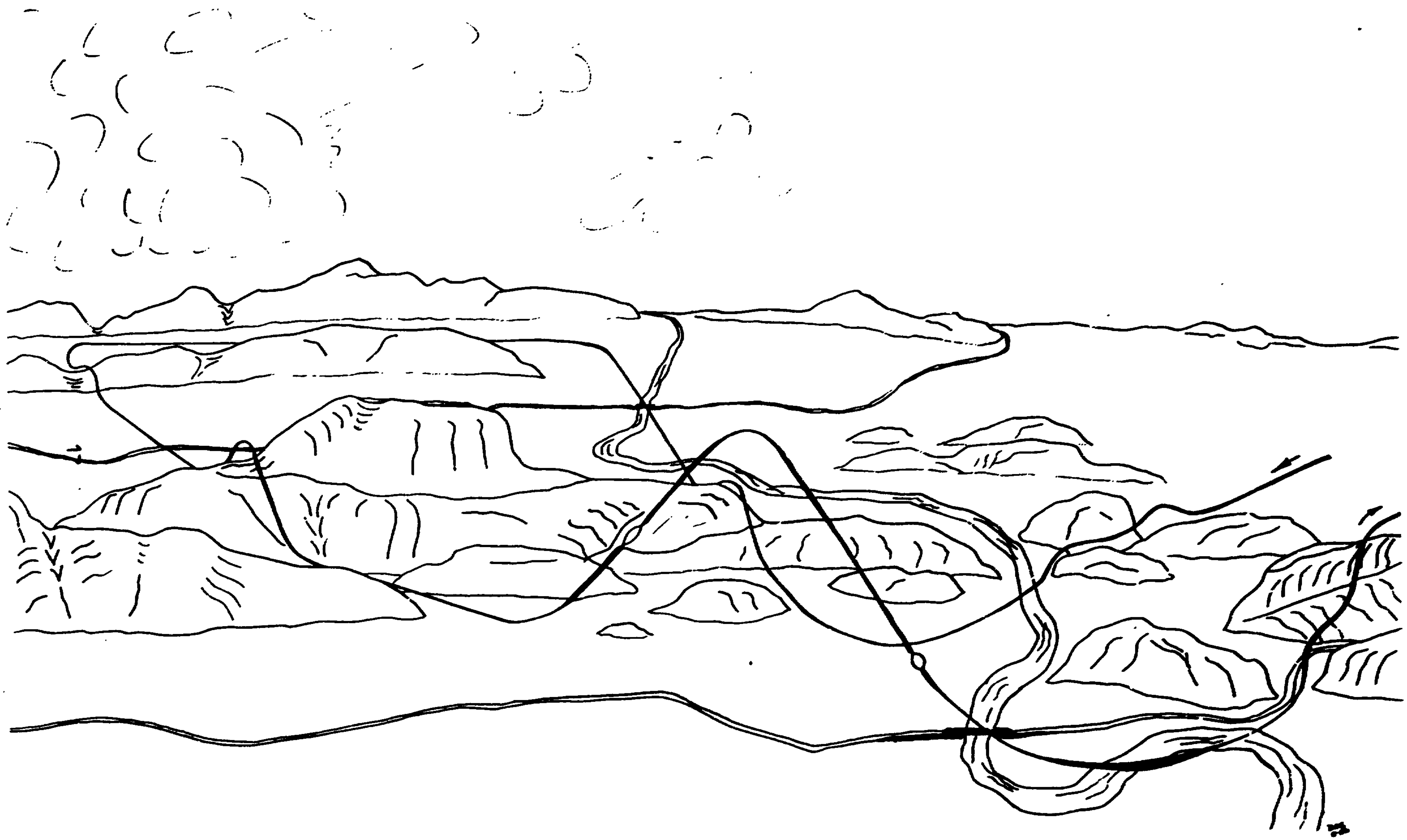

Figure 4 Mission 11 (21), Low Level Navigation (Artist Concept)

Figure 5 Mission 13 (23) Hard Turns at Low Altitude (Artist's Concept)

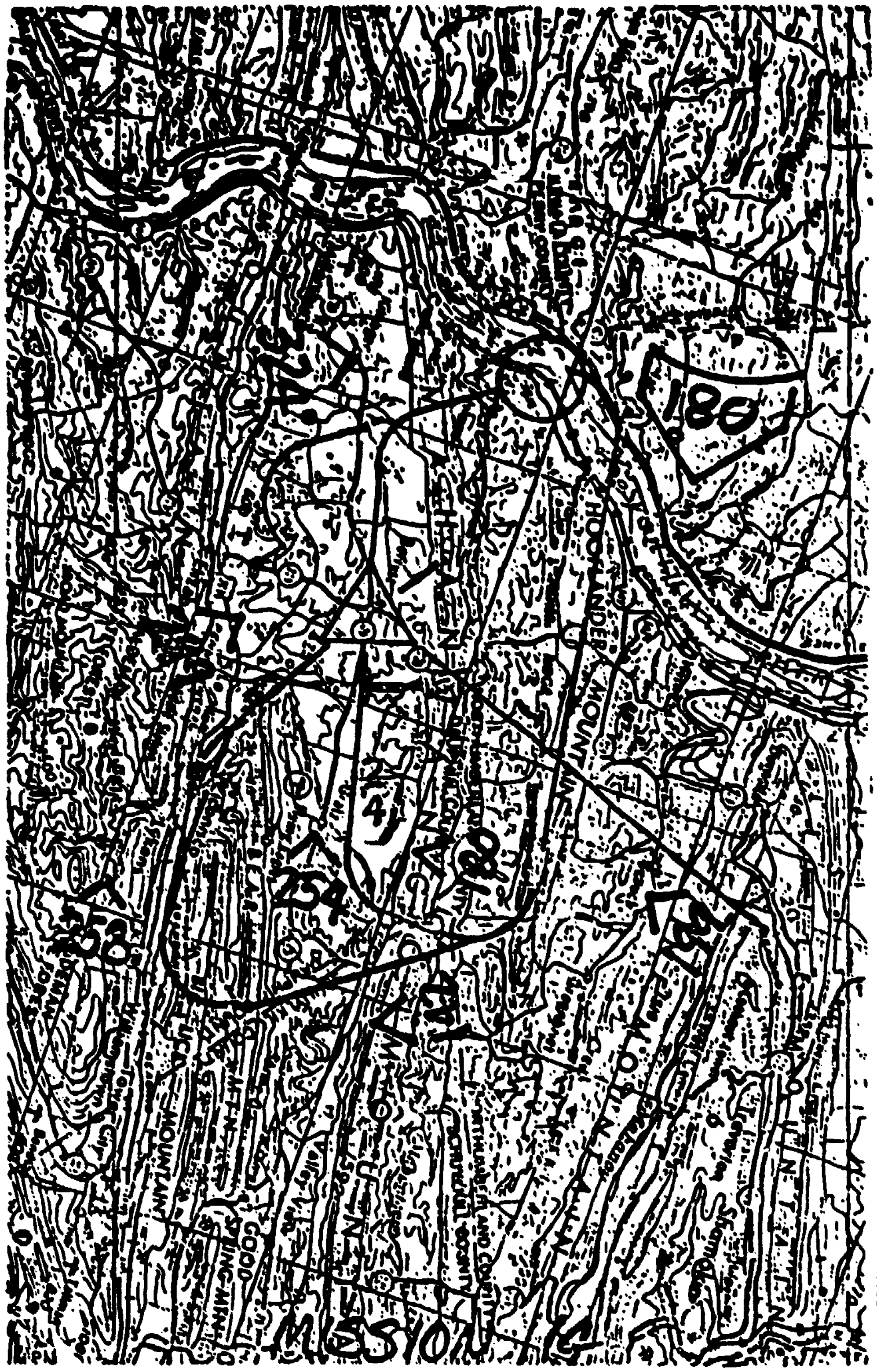

Figure 6 Mission 14

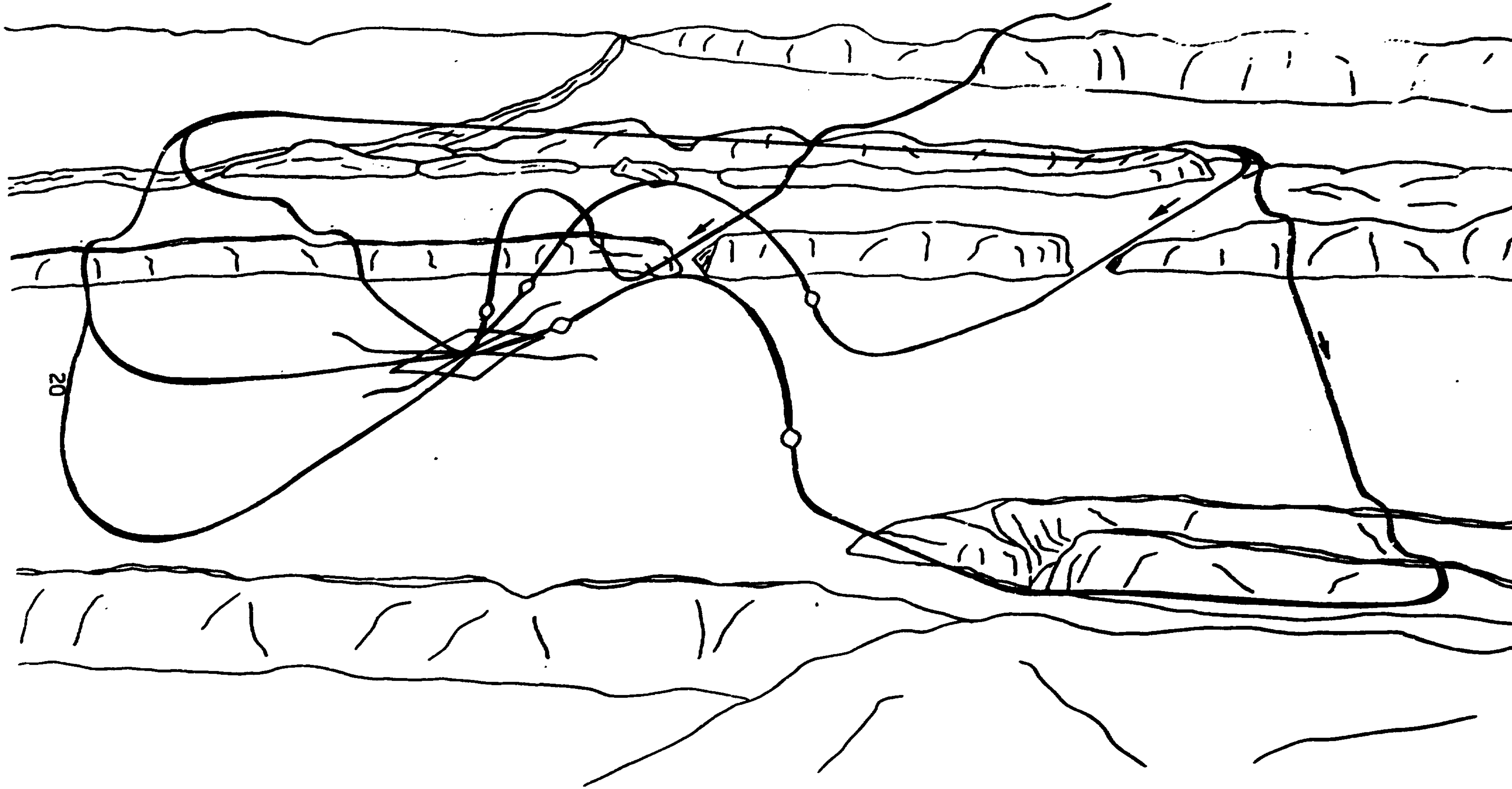

Figure 7 Mission 14 (24) Range Mission (Artist's Concept)

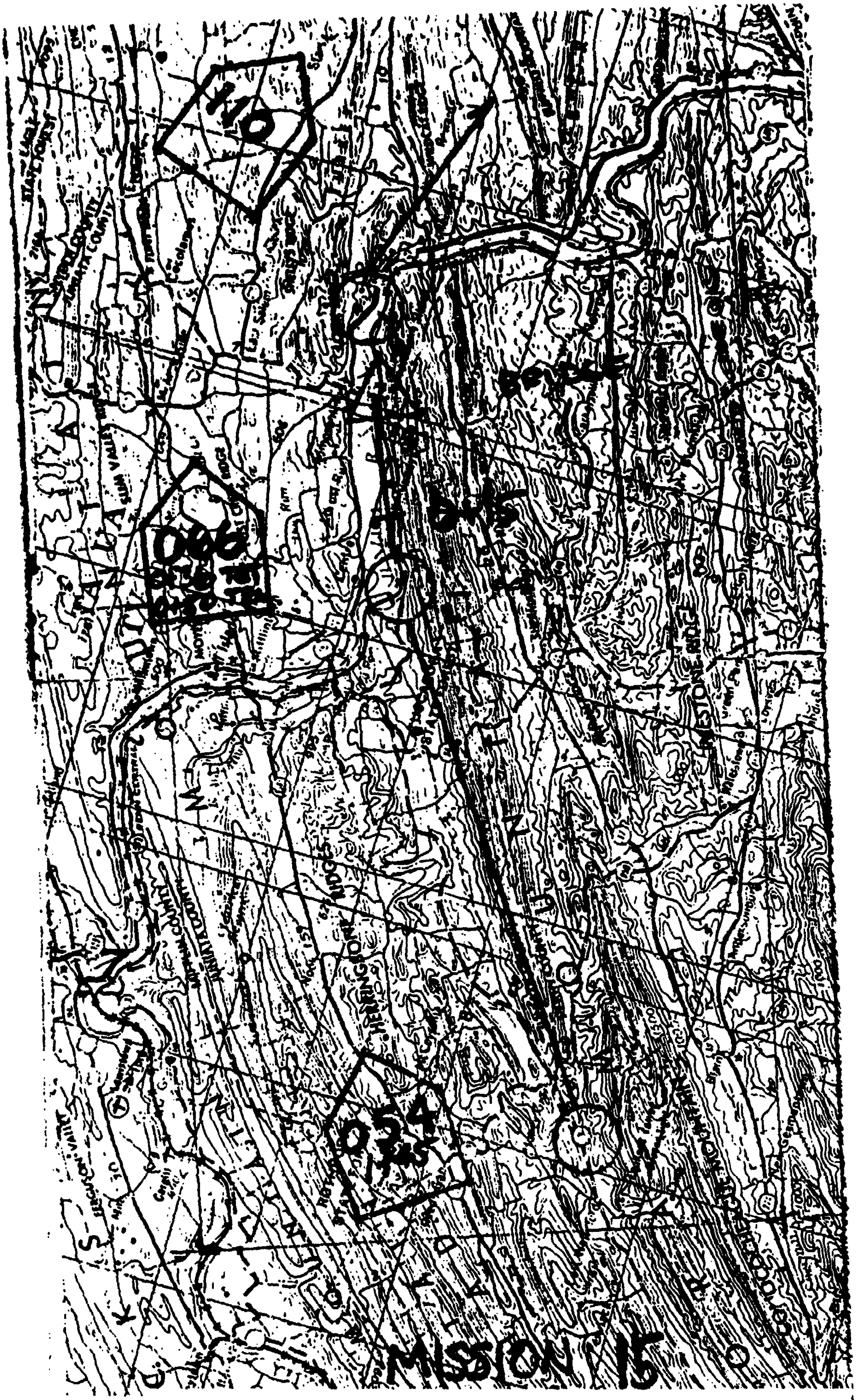

Figure 8. Mission 15

Figure 8a. Mission 15 (continued)

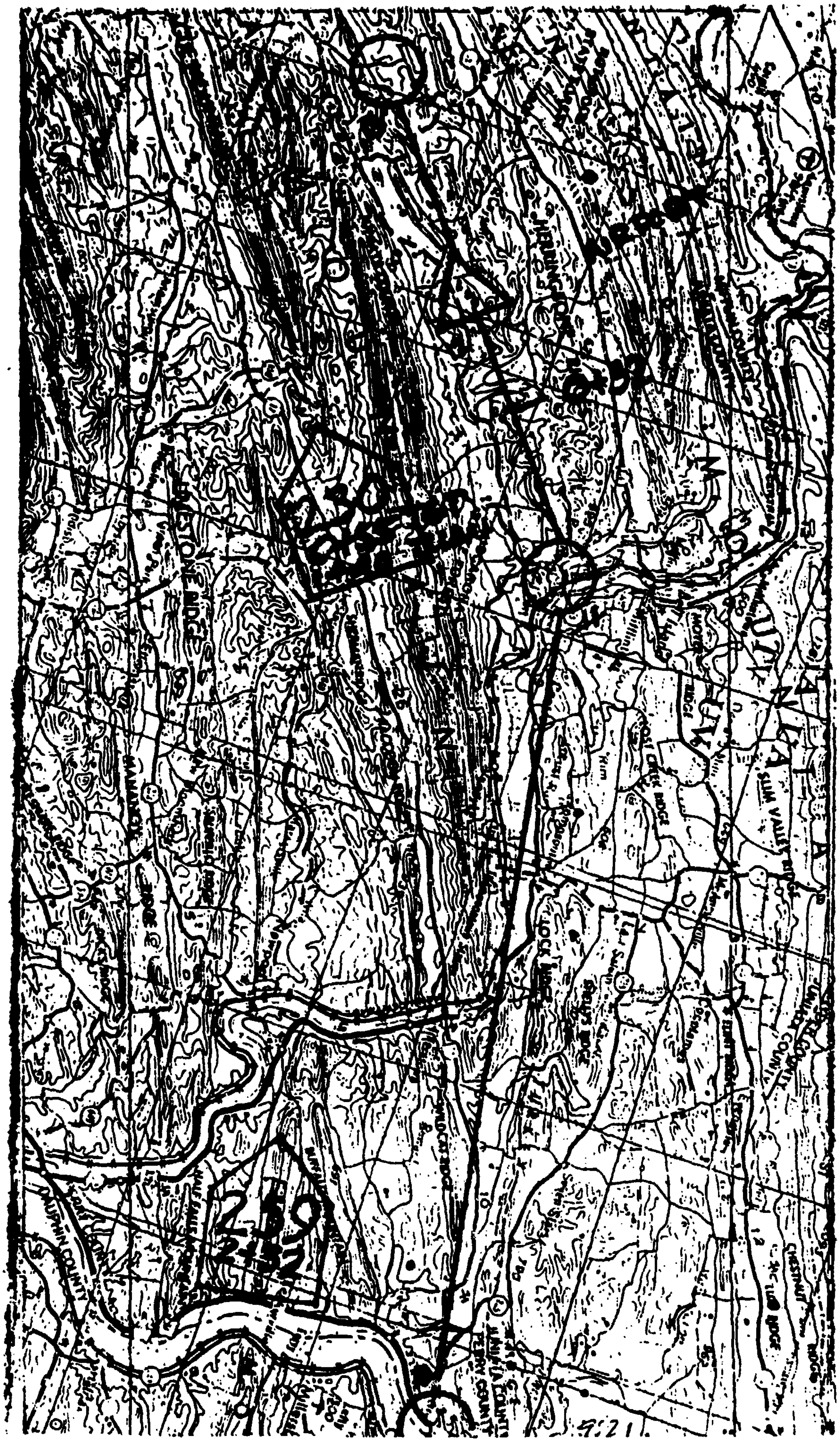

Figure 8b. Mission 15 (continued)

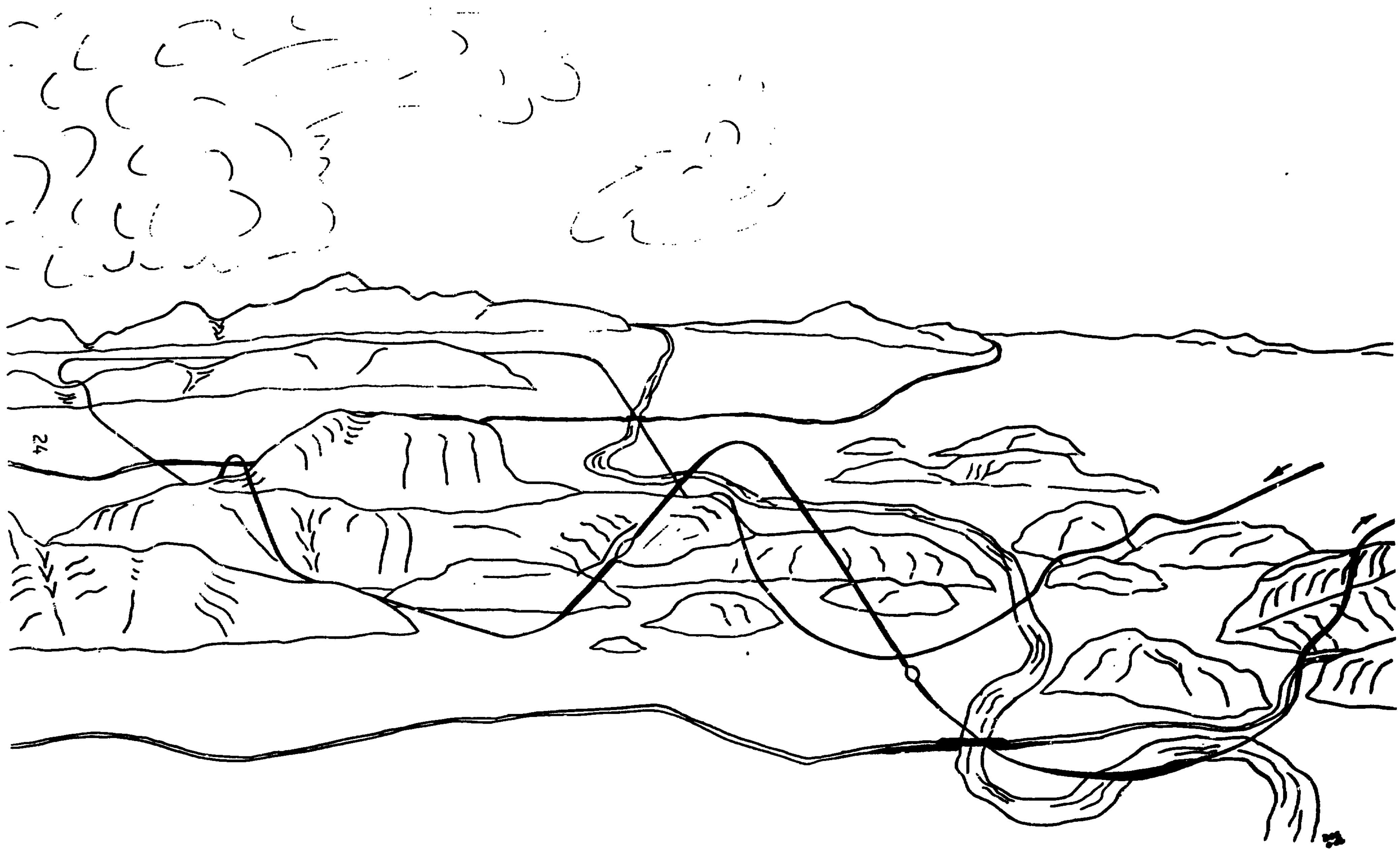

Figure 9 Mission 15 (25) Pop-up Weapon's Delivery (Artist's Concept)

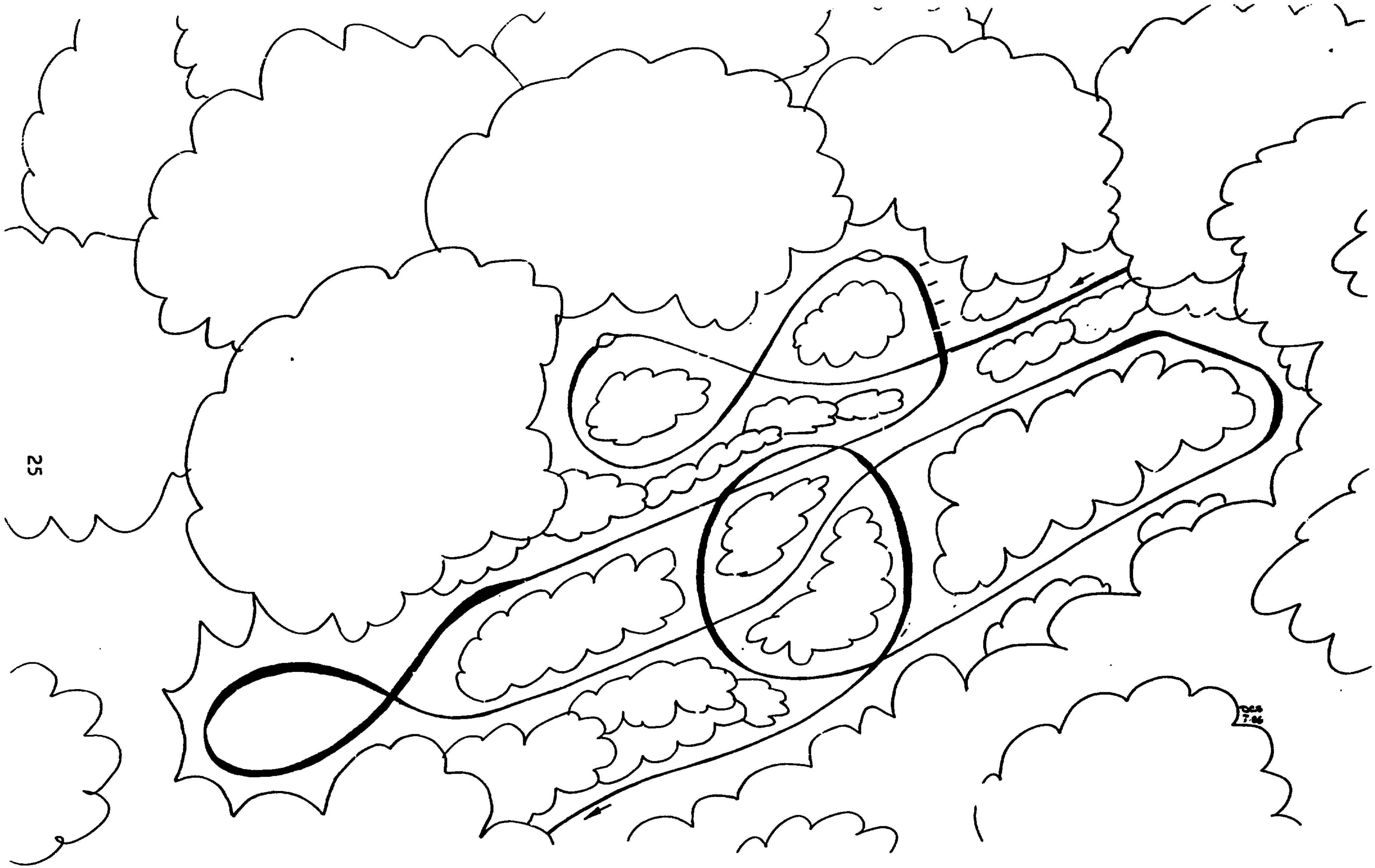

Figure 10 Mission 16 (26) IMC Maneuvering (Artist's Concept)

SECTION III

STUDY RESULTS

1. PERFORMANCE DATA

Table 3 shows the mean pilot response time for making a control input following a GCAS warning for individual missions and across all experimental conditions. Of 220 warnings there were 208 warnings that elicited a control response from the pilots. The 12 warnings that did not result in a control input were too brief for pilot response or were ignored for various reasons that will be discussed later. The overall mean response time was 0.66 seconds with a standard deviation of 0.30.

The size of the standard deviation indicates a departure from a normal distribution. In order to determine the extent of the departure, a graph of the frequency distribution was drawn (Figure 11), and it shows a positive skewness in the distribution (shaded area) of pilot response times. Further inspection of these data reveals that approximately 80 percent of the area (10 out of 13 cases) in the tail of the distribution is from mission 16 (IMC/unusual attitudes), where the pilots were induced into a disorienting environment, which no doubt contributed to the longer and somewhat atypical response times. Almost 25 percent of the experimental runs on mission 16 resulted in pilot disorientation which was more frequent than initially thought possible and provided valuable data for analysis of GCAS. In order to compensate for the skewed distribution, the median and semi-interquartile range (Q) were computed to use as a basis for determining the time allowance for pilot response time in the GCAS algorithm. In actuality, the difference between using the mean and median in this case is probably only of academic interest. If you use

TABLE 3

TABLE SHOWING PILOT RESPONSE TIMES (SECONDS) FOR STICK INPUT

FOLLOWING GCAS WARNING

MISSION	MEAN TIME (SECONDS)	S.D.	N
11 (LO LEVEL NAV)	0.53	0.31	30
12 (IMC/LOW SPEED)	0.62	0.28	30
13 (LO ALT TURN)	0.57	0.22	22
14 (RANGE)	0.66	0.26	54
15 (LO LEVEL BOMB/NAV)	0.64	0.27	26
16 (IMC UNUSUAL ALTITUDES)	0.86	0.39	46
ACROSS ALL MISSIONS:	M = 0.66	S.D. = 0.30	N = 208

TABLE 4

ANALYSIS OF VARIANCE (ANOVA) OF PILOT RESPONSE TIME (SECONDS)

FROM GCAS WARNING TO CONTROL PILOT

SOURCE	SUM SQ	DEGREES OF FREEDOM	MEAN SQ	F-RATIO
MISSION NO.	24.6	5	4.92	5.38
ERROR	184.8	202	0.91	
TOTAL	209.4	207		

*LEVEL OF SIGNIFICANCE < 0.001

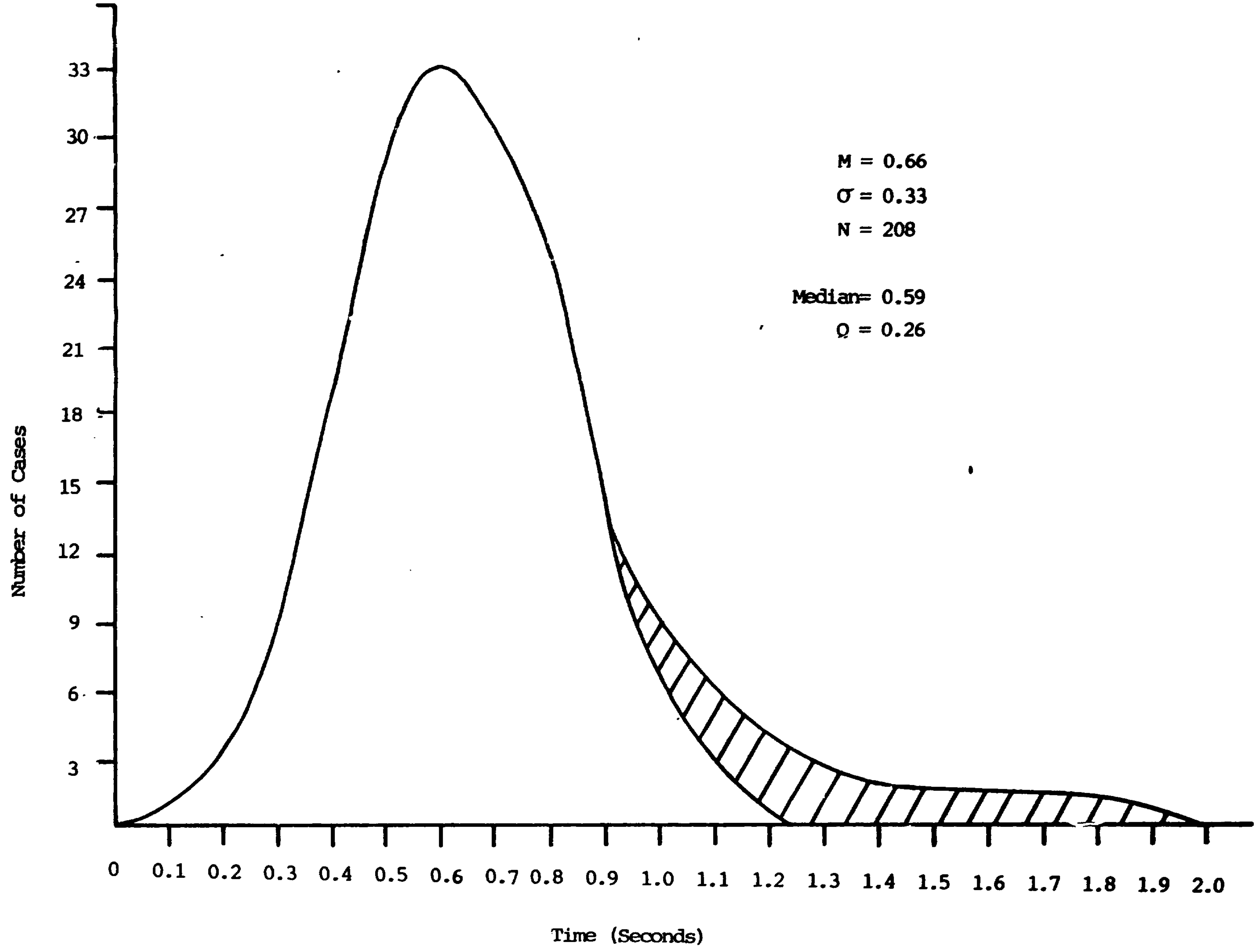

Figure 11 Frequency Distribution of Pilot Response Times for Control Input

the median to generate a pilot population value, the recommended time to allow for pilot response time would be 1.11 seconds (0.59 median value plus twice the 0.26 Q value) versus 1.25 using the mean and standard deviation (0.66 mean value plus twice the 0.30 S.D. value). The authors recommend the 1.25-second interval in this case to allow for the possibility of pilot disorientation or distraction in some situations. This probably represents a good compromise between allowing the operator some flexibility without a significant increase in nuisance warnings.

In comparing the mean response times in Table 3, we see that missions 11 and 13 yield the lowest average response times (0.53 seconds and 0.57 seconds respectively), followed by missions 12, 14, and 15 with slightly higher response times (0.62, 0.64 and 0.66 seconds) and finally mission 16 with a relatively large mean response time (0.86 seconds). Analysis of variance performed on these data indicate the differences are statistically significant at less than the 0.001 level (Table 4). The significance was undoubtedly due to mission 16, which was discussed earlier.

The standard deviations for the individual missions in Table 3 are slightly larger than you would get in a normal distribution showing increased variability and possibly some skewdness. The distributions for mission 11 through 15 are symmetrical, with mission 16 showing the skew previously mentioned.

Of the twelve warnings that did not elicit a response, two were too brief for the pilot to respond, four were ignored because the pilot was in the midst of weapon delivery, two were coincidental with the pilot's recovery, and four warnings were considered invalid.

A summary of warning duration times is shown in Table 5 and provides some interesting insights on GCAS. Mean warning duration was 3.1 seconds with a standard deviation of 2.34. The relative size of the S.D. is even greater than in the response time data, indicating even more variability and skewdness (Figure 12). In this instance, the skew is generated from two sources - mission 12 and mission 16. The reason for the larger mean and S.D. on mission 16 (induced disorientation) was discussed earlier and requires no further comment.

Mission 12 was a low speed maneuvering flight under instrument meteorlogical conditions (IMC) and was inserted into the study to assess the low speed characteristic of GCAS. The extremely large mean 5.60-second warning duration is due to the fact that all warning situations on mission 12 resulted in a crash and the conditions necessary to silence the voice warnings were never fulfilled. The crashes are attributed to the method of computing terrain rise, altitude loss and the resulting pilot response times. A comprehensive analysis of the algorithm is covered in greater detail later in the results section. It is sufficient to say at this point that changes to the algorithm will be required to afford some protection in the straight and level flight regime. One final point on mission 12, an offline analysis of the algorithm showed that slope of the terrain was not a factor in any of the crashes. The Analysis of Variance of the warning duration data (Table 6) verifies the mean differences in tables are significant and are obviously due to missions 12 and 16.

One of the factors that can be crutial to the success of a GCAS is how long it takes a pilot to get maximum G's on the aircraft - the quicker you can get to maximum G, the less altitude lost. Table 7 summarizes the mean time to maximum G data. The pattern of these data is similar to measures discussed earlier - slightly larger than average variability, and some skewdness with mission 16 accounting for most of

TABLE 5

MEAN WARNING DURATION TIMES

MISSION	MEAN TIME(SECONDS)	S.D.	N
11 (LO LEVEL)	1.85	1.08	32
12 (IMC/LOW SPEED)	5.68	1.39	31
13 (LO ALT TURN)	1.50	0.94	22
14 (RANGE)	2.32	2.19	58
15 (LO LEVEL BOMB/NAV)	2.28	1.47	26
16 (IMC UNUSUAL ATTITUDES)	4.38	2.49	51
ACROSS ALL MISSIONS:	M = 3.10	S.D. = 2.34	N = 220

TABLE 6

ANALYSIS OF VARIANCE FOR WARNING DURATION TIMES

SOURCE	SUM SQ	DEGREES OF FREEDOM	MEAN SQ	F-RATIO
MISSION NO.	4986	5	897	25.59
ERROR	7503	214	35	
TOTAL	11989	219		

* LEVEL OF SIGNIFICANCE < 0.001

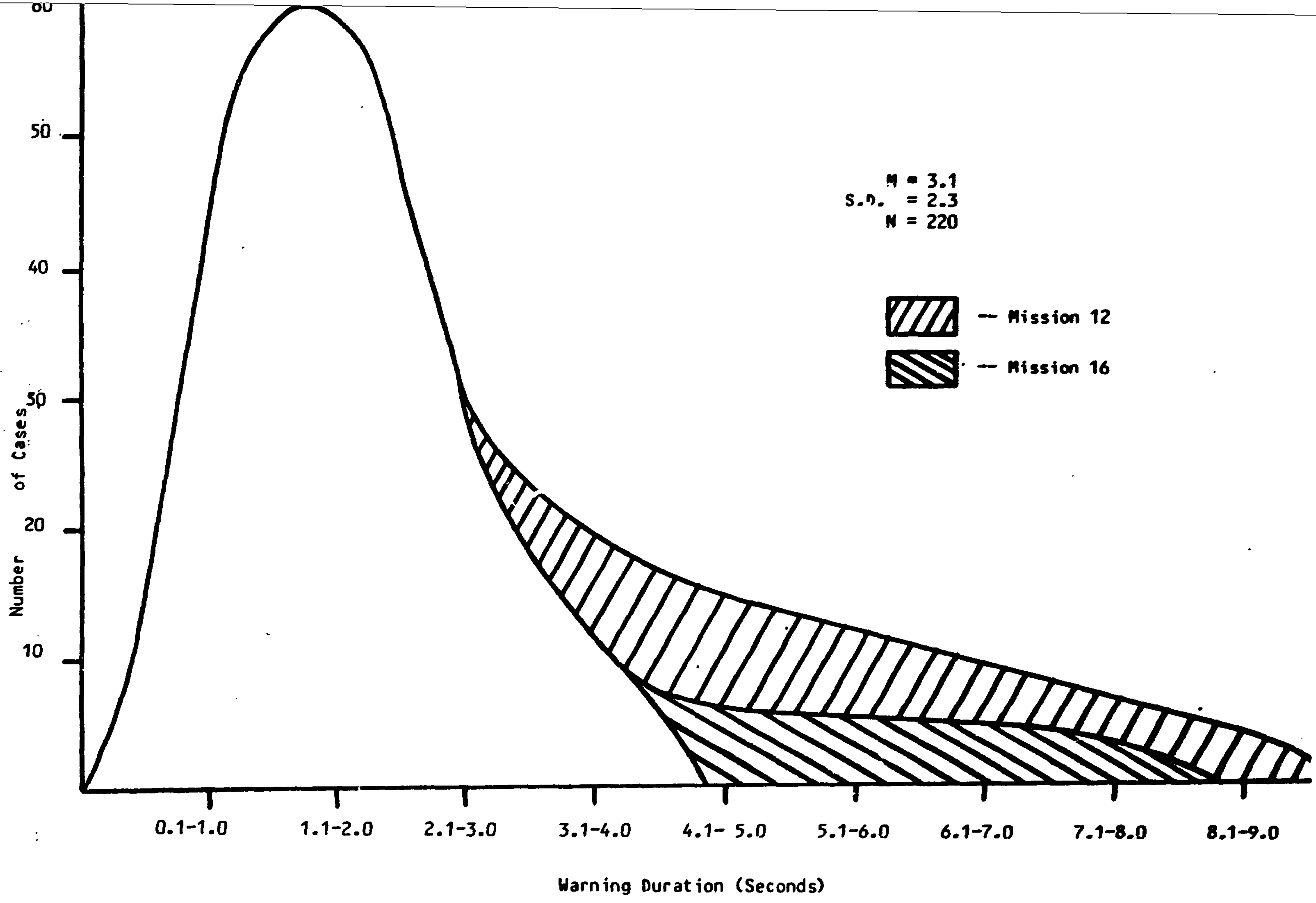

Figure 12. Frequency Distribution of Warning Duration

TABLE 7

MEAN TIME TO MAXIMUM G'S

MISSION	MEAN TIME(SECONDS)	S.D.	N
11 (LO LEVEL NAV)	1.86	0.89	32
12 (IMC/LOW SPEED)	2.73	1.42	31
13 (LO ALT TURN)	2.16	0.63	18
14 (RANGE)	2.27	1.14	56
15 (LO LEVEL BOMB/NAV)	2.62	1.11	25
16 (IMC UNUSUAL ATTITUDES)	3.80	1.50	51
ACROSS ALL MISSIONS: M = 2.68		S.D.= 1.39	N = 213

TABLE 8

ANALYSIS OF VARIANCE FOR MEAN TIME TO MAXIMUM G'S

SOURCE	SUM SQ	DEGREES OF FREEDOM	MEAN SQ	F-RATIO
MISSION NO.	991	5	198	13.20
ERROR	3093	207	15	
TOTAL	4084	212		

* LEVEL OF SIGNIFICANCE < 0.001

it. The overall mean time to maximum G is 2.68 seconds with a S.D. of 1.39. Missions 11 through 15 are grouped with small differences between them, while mission 16 is significantly larger (Table 8). We should be somewhat cautious in interpretting 'G' onset data in fighter simulators, since they cannot simulate the physical sensation of anything above 1 G. It is possible that 'G' onset may be quicker in a simulator than in an actual aircraft. However, the F-16 force stick would, in the opinion of the authors, more likely be representative than a simulator with a displacement stick. In any case, the simulator data is probably representative of the actual aircraft, but flight test data should be used to verify this.

Table 9 depicts mean maximum G across missions. The mean values range from 2.32 for mission 12, to 5.9 for mission 16. Unlike other data distributions, maximum G standard deviations are quite small in relation to their respective means, reflecting normal symmetrical and tight groupings. Mean differences between all these individual missions are significant (Table 10). The maximum G data reflects the maneuvers required on each mission. The relatively low G's on mission 12 (2.32) are all the G's available to the pilot on a low speed zero flight path angle mission; whereas 5.9 G mean seen in mission 16 is representative of IMC aerobatic mission. Although we must not take simulator G data too literally, the figures in this case appear to match those typically encountered in actual aircraft.

The final group of flight parameter data analyzed was mean time to zero flight path angle (FPA) (Table 11). The total N in this case was somewhat reduced since the data from mission 12 were not applicable, since zero FPA was never achieved. The only significant data shown are that the mission 16 mean is much larger than the others, both because

TABLE 9

MEAN MAXIMUM G'S ACROSS MISSIONS

MISSION	MAXIMUM G	S.D.	N
11 (LO LEVEL NAV)	3.38	0.98	32
12 (IMC/LOW SPEED)	2.32	0.34	31
13 (LO ALT TURN)	5.52	1.62	22
14 (RANGE)	4.86	1.81	58
15 (LO LEVEL BOMB/NAV)	5.15	1.96	26
16 (IMC UNUSUAL ATTITUDES)	5.90	1.11	51
ACROSS ALL MISSIONS:	M = 4.62	S.D. = 2.34	N = 22

TABLE 10

ANALYSIS OF VARIANCE FOR MEAN MAXIMUM G'S ACROSS MISSIONS

SOURCE	SUM SQ	DEGREES OF FREEDOM	MEAN SQ	F-RATIO
MISSION NO.	3270	5	654.0	32.22
ERROR	4350	214	20.3	
TOTAL	7620	219		

* LEVEL OF SIGNIFICANCE < 0.001

of the complex maneuvers and the induced disorientation (Table 12). Almost 30 percent of the GCAS events observed in the study resulted in simulated crashes. A statistical summary of these crashes is shown in Table 13. Almost one-half the crashes occurred on mission 12 and were due to the way the GCAS algorithm is mechanized. This will be covered in the Algorithm Analysis. Of the remaining 33 crashes, 21 occurred on bombing type missions where the pilots tended to ignore the warning until weapons delivery was completed, and six occurred during aerobatics where disorientation was a factor.

One reason pilots flew through the warnings involved how frequently they occurred at an obviously high altitude, especially at the higher dive angles where pilots were trying to release at the briefed altitude of 2500 feet. When warnings occurred at 3000 feet and above, they would have to make a judgement: was the warning early or was it caused by a higher than normal dive angle? This required time and concentration at a point in the delivery where intense concentration was required as the delivery solution. This problem is not unique to the air-to-ground delivery mission; in fact, it is one faced by pilots on almost every run in an unfamiliar target area. In an operational sense, the tendency to fly through a warning will surely be less in an aircraft than it was in a simulator, and pilots will at least take a second look at the situation when the warnings occur. In this same view, however, the system will lead to occasional early pull-ups and subsequent dry passes.

Probably the most significant problems were those encountered in mission 12, where all warnings led to crashes and on other missions where rising terrain was encountered in a near level flight attitude. In these cases, pilots received late warnings or none at all. The underlying causes of this problem are described in Section 3, Algorithm Analysis

TABLE 11

MEAN TIME TO ZERO FLIGHT PATH ANGLE

MISSION	MEAN TIME (SECONDS)	S.D.	N
11 (LO LEVEL NAV)	2.06	1.19	22
12 (IMC/LOW SPEED)	N/A	N/A	N/A
13 (LO ALT TURN)	2.36	0.79	22
14 (RANGE)	2.72	1.30	38
15 (LO LEVEL BOMB/NAV)	2.73	1.73	21
16 (IMC UNUSUAL ATTITUDES)	7.20	1.73	43
ACROSS ALL MISSIONS:	M = 3.88	S.D. = 2.56	N = 146

TABLE 12

ANALYSIS OF VARIANCE MEAN TIME TO ZERO FLIGHT PATH ANGLE

SOURCE	SUM SQ	DEGREES OF FREEDOM	MEAN SQ	F-RATIO
MISSION NO.	67650	4	16912	89.7
ERROR	26583	141	188	
TOTAL	94233	145		

* LEVEL OF SIGNIFICANCE < 0.001

TABLE 13

SUMMARY OF CRASH DATA

	NO. CRASHES	NO. WARNINGS	PERCENT OF MISSION	PERCENT OF TOTAL
MISSION 11	5	32	16	8
MISSION 12	31	31	100	48
MISSION 13	1	22	5	2
MISSION 14	14	58	24	22
MISSION 15	7	26	27	11
MISSION 16	6	51	12	9
TOTAL:	64	220	N/A	100

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MISSION 16	6	51	12	9
TOTAL:	64	220	N/A	100

(in 3.a Condition 1 and 3.c). Basically, the problem stems from system inhibits installed to prevent nuisance warnings during ridge crossings and it is one which will be extremely difficult to solve. If the inhibits are removed to provide a "look ahead" or terrain projection capability, nuisance warnings go down; if the inhibits are used, there is little or no protection against rising terrain.

2. QUESTIONNAIRE DATA

Pilot ratings on all aspects of operational utility were overwhelmingly favorable towards GCAS. These ratings are summarized in Table 14. Eight out of ten pilots thought the warnings were timely and the system was either useful or extremely useful in terms of system utility. These same pilots also said they got nuisance warnings occasionally, did not tend to over rely on the warnings, and missed no warnings. All participants agreed the attention getting value of GCAS was good. Although all pilots thought the system was either good or satisfactory, they all agreed some improvements were required.

In the way of system improvement, there was general agreement (6 out of 10) that ridge crossings presented a problem and require an algorithm to modify and improve the GCAS in this situation. Two pilots reported that they would like a system with some foward looking capability. Some sort of anticipatory cue prior to the warning was suggested by three of the pilots. Finally, one pilot suggested a "more timely" voice.

General comments made by the pilots were all favorable and two thought GCAS should be installed immediately. Six out of ten pilots thought the slope warning unnecessary, two thought it moderately useful, one preferred it, and one made no comment. Finally, the pilots generally agreed that the simulation was satisfactory for rating GCAS. If the reader is interested in reading all pilot comments, they are provided in the Appendix.

TABLE 14

QUESTIONNAIRE DATA SUMMARY

TIMELINESS:

2/10 SLIGHTLY EARLY
7/10 JUST RIGHT
1/10 SLIGHTLY LATE

ATTENTION GETTING VALUE:

5/10 ALL THE TIME
5/10 MOST OF THE TIME

NUISANCE WARNING OCCURRENCE:

8/10 OCCASIONALLY
2/10 MOST OF THE TIME

MISSED WARNINGS:

8/10 NONE
2/10 YES

SYSTEM UTILITY:

8/10 USEFUL OR EXTREMELY USEFUL
2/10 MODERATE USEFULNESS

OVER RELIANCE ON WARNING:

8/10 SELDOM OR NEVER
1/10 OCCASIONALLY
1/10 FREQUENTLY

ADEQUACY/SUITABILITY:

8/10 SATISFACTORY, BUT NEEDS IMPROVEMENT
2/10 GOOD OR VERY GOOD

3. ALGORITHM ANALYSIS

The GCAS algorithm was analyzed by CSDF in order to determine the validity of warnings in various flight conditions. For the purpose of this evaluation, an invalid warning is one which occurs too early (a "nuisance" warning), or one which occurs too late for a safe recovery. The algorithm is briefly explained here in order to provide a background for the analysis. Cubic's algorithm continuously compares the aircraft's present height above the ground with the altitude required for dive recovery. The algorithm predicts altitude loss during dive recovery as a sum of the following:

a. Altitude loss due to terrain rise during the pull-up.

b. Altitude loss due to pilot response time.

c. Altitude loss during roll recovery.

d. Altitude loss during a 5-G pull-up.

Figure 13 illustrates this piecewise calculation of altitude loss.

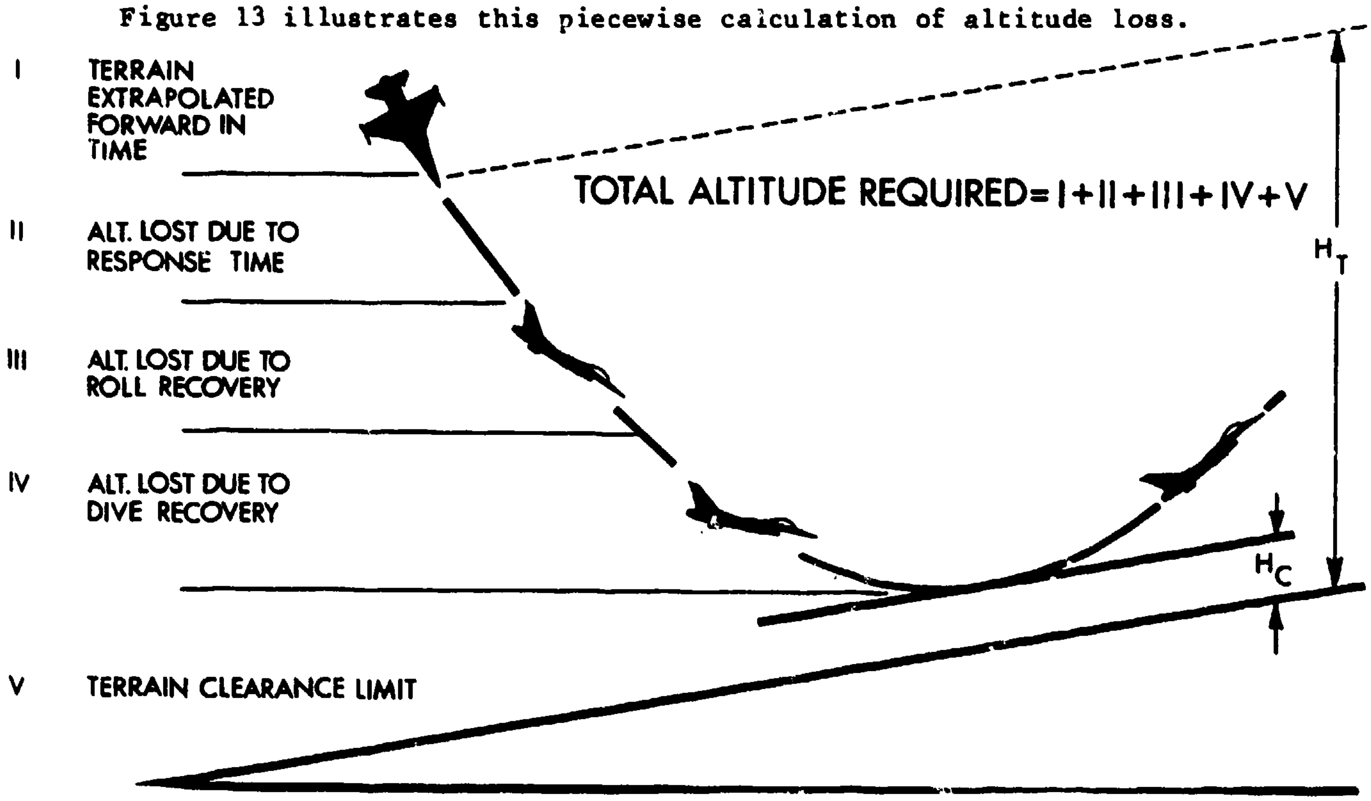


Figure 13. Piecewise Calculation of Altitude Loss

The following paragraphs describe each portion of the altitude loss calculation in detail. Reasons for early or late warnings are also discussed.

a. Altitude loss-pilot response

The initial portion of the altitude loss is fairly simple to compute. During the period of time before the pilot has made any response to a warning, the aircraft is projected to continue its present vertical trajectory. The current vertical velocity is multiplied by a computed response time (T_{resp}) to calculate altitude that would be lost from warning to initial stick input.

NOTE: If the altitude loss is negative (i.e., the airplane climbing the absolute value of the altitude loss is used), Cubic assumed a basic response time of two seconds and modified it by several conditions:

Condition 1 : Small Dive Climb Angle (GAMMA)

In order to reduce the possibility of early warnings during ridge crossings T_{resp} is reduced when the aircraft is in level or near level flight. The following relation is used:

$$\text{If } \gamma \leq 5^\circ$$

$$T_{resp} = 0.4$$

So at zero flight path angle, $T_{resp} = 0$

Condition 2 : Roll Angle/Roll Rate (ϕ, $\dot{\phi}$) is assumed that if the pilot is rolling out of a bank at the time a warning occurs, his reaction time will be less, so:

If $\dot{\phi} > 15$ deg/sec

and

ϕ and $\dot{\phi}$ are of opposite sign,

$T_{resp} = 0.3$ sec

NOTE: This condition overrides Condition 1.

Condition 3 : Vertical Velocity, Vertical Acceleration. Response time is assumed to be shorter when the pilot is already reducing his downward velocity. So, whenever the aircraft has a downward flight path ($V_z \leq 0$) and a positive acceleration vertical acceleration ($A_z \leq 0$), the response time used in calculating the airplane's future flight path angle is reduced by half. Otherwise, if the airplane has a downward acceleration, its vertical velocity will be modified using full response time as calculated by Conditions 1 and 2. So the extrapolated dive/climb angle, γ_{ext} is calculated as follows:

$$\gamma_{ext} = \tan^{-1}\left[\frac{V_{z(ext)}}{Vx}\right]$$

where $V_{z(ext)} = V_z + A_z(T_{ext}$ = extrapolated vertical velocity)

$T_{ext} = T_{resp}$ (modified by Condition 3)

V_x = Horizontal Velocity

The value γ_{ext} is used in computing the altitude required for a 5-G (cr available G) dive recovery (Paragraph C). If the airplane has a positive vertical velocity and a positive vertical acceleration, the extrapolation is not performed. Additionally, if $\gamma_{ext} > 0$, no (positive) altitude change will be calculated due to pilot response time.

Condition 4 : Previous warning within 3 seconds. It is assumed that if a pilot has recently (within the past 3 seconds) experienced a pull-up warning, he will react to subsequent warnings more quickly. Thus, if the warning is not on and less than 3 seconds have elapsed since the last warning ceased,

$$T_{resp} = 1.5 \text{ seconds}$$

Condition 5 : Warning in progress. When a pull-up warning is in effect, the response time is reduced by one time step each time the calculation is performed.

So, for the basic 2 second response time, T_{resp} will be reduced to zero after 2 seconds of warning.

a.1 Problems

a.1.1 Early warnings

a.1.1.1 The basic response time of 2 seconds is too long. A more realistic baseline would be between 1 and 1.25 seconds (see performance section of results).

a.1.1.2 The establishment of a 0.3 second response time under Condition 2 is intended to reduce nuisance warnings. In some cases, however, it actually causes an increase in invalid warnings. Consider first the case where a pilot gets a warning during descending turn ($\dot{\gamma} > 5°$). His response time (T_{resp}) starts at a value of 2 seconds.

As he begins to roll out of his turn, Condition 2 immediately reduces his response time to 0.3 seconds. This will often cause the alarm to terminate since altitude loss due to response time has decreased. However, as soon as (a) his roll rate falls below 15 degrees per second or (b) his bank angle changes sign because he overshoots wings level, the response time resets to 1.5 seconds (Condition 4). This can cause the warning to come back on even though he has begun a satisfactory recovery. Modifications to altitude loss based on roll rate would perhaps be more appropriately applied to the roll recovery portion of the algorithm.

It would also be prudent to suppress response time reset (Condition 4) completely for 3.0 seconds after a warning has been satisfied. As a minimum, it should be reset to a much smaller value than 1.5 seconds.

a.1.1.3 It is not valid to assume, as in condition 1, that a pilot's response time is less in level (γ = 0) flight. The response times demonstrated in this study showed no substantial reduction under these conditions. In level flight, the only source of a ground collision can be ground rise. Paragraph a. shows that this algorithm does not consider pilot response time in calculating altitude loss due to terrain rise. Therefore, Condition 1 provides only a negligible reduction in nuisance warnings during ridge crossings.

a.1.1.4 Condition 3 modifies the airplane's predicted altitude loss according to instantaneous vertical velocity and acceleration. It can cause abrupt changes in the predicted altitude loss as the aircraft transitions from one set of conditions to another, resulting in erroneous warning resets in a manner similar to the example in paragraph a1.1.2. Also, since the flight path is never extrapolated upward during a climbing maneuver, some needless warnings may occur (Figure 14).

Consider the case where a pilot is pulling up to avoid a ridgeline. The algorithm projects zero altitude gain during the response time. So even though the pilot may be climbing and accelerating upward, he will get a warning based on the fact that his current altitude is less than the projected terrain height. This is compounded by the fact that the time used for calculating terrain rise is based on dive recovery time. A positive dive recovery time will be calculated even though the airplane's flight path is above the projected terrain (Paragraph d).

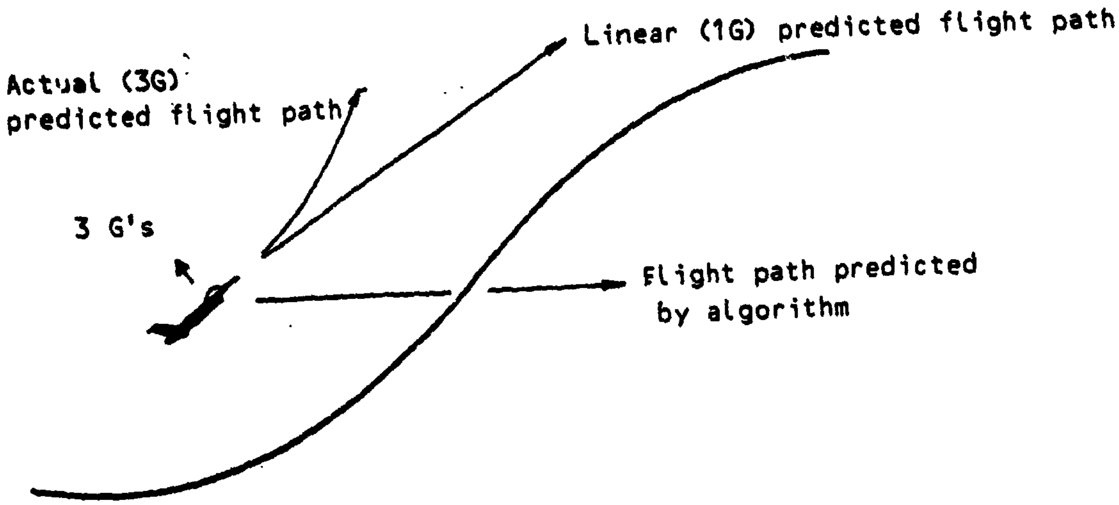


Figure 14. Possible Nuisance Warning Caused by Failure to Project Flight Path Upward

A more accurate way to approximate the altitude loss during pilot response time would be to simply apply the following equation to obtain altitude lost during pilot response. That is:

$$\Delta Z_{resp} = \frac{-V}{\dot{\gamma}_1} \operatorname{Cos} (\gamma) \Big|_{\gamma_1}^{\gamma_2}$$

where:

$$\gamma_1 = \text{Present flight path angle}$$

$$\gamma_2 = \gamma_1 + \dot{\gamma}_1 \ (T_{resp})$$

$$V = \text{Aircraft Velocity}$$

and, assuming relatively small change in $\dot{\gamma}$,

$$\dot{\gamma}_1 = \frac{g}{V} \ (n_v - \cos \gamma_1)$$

$$n_v = n \cos \phi$$

This simple equation provides both altitude loss (or gain) during pilot reaction time and a predicted flight path angle to be used in the dive recovery equations. It eliminates abrupt changes in predicted loss and resultant nuisance warnings that are characteristic of the current algorithm.

b. Altitude Loss During Roll Recovery

The GCAS algorithm predicts the altitude that will be lost while the pilot rolls wings level. This calculation is based on the assumption that the pilot will not begin his dive recovery until he has brought his wings nearly level. The calculation is made in the following manner:

(1) The time for roll recovery is calculated.

$$T_{rr} = \frac{|\phi| - 20^\circ}{\dot{\phi}\ pred}$$

Where ϕ = roll angle

$\dot{\phi}$ pred = predicted roll rate

= 70 °/Sec for 20 ° < 0 < 85 °

56 °/Sec for 85 ° < 0 <145 °

90 °/Sec for 145 °< 0 <180 °

(2) The vertical velocity is extrapolated

$$V_{rr} = V_z + A_z \cdot T_{rr}$$

where

V_{rr} = Extrapolated vertical velocity

V_z = Instantaneous (measured) vertical velocity

A_z = Instantaneous (measured) vertical acceleration

(3) The flight path angle is extrapolated:

$$\gamma_{rr} = \tan^{-1} \left[\frac{V_{rr}}{V_x} \right]$$

Where V_x = Instantaneous horizontal velocity

(4) The altitude loss due to roll recovery is calculated.

$$\Delta Z_{rr} = V_z \cdot T_{rr}$$

If the altitude loss is negative (i.e. a climb), the absolute value $|\Delta Z_{rr}|$, is used.

If the extrapolated flight path (γ_{rr}) is greater than zero or If the absolute value of the roll rate is greater than 80 °/Sec,

then ΔZ_{rr} is set to zero.

b.1 Problems

b.1.1 Early warnings

b.1.1.1 The algorithm assumes incorrectly that no dive recovery begins until roll recovery is complete. In fact, test results showed that pilots reduced bank and applied recovery "G" simultaneously. In cases where the aircraft is in a high "G" turn merely rolling out of the bank while maintaining the "G" affected most recoveries.

b.1.1.2 The use of three distinct roll rates for predicting roll recovery times causes abrupt changes in the altitude loss prediction. For instance, the algorithm would predict a T_{rr} of 0.91 seconds for a bank angle of 84°. By increasing the bank to 85°, T_{rr} jumps to 1.2 seconds. Decreasing the bank from 145° to 144° causes T_{rr} to change from 2.2 seconds to 1.4 seconds. At 450 knots and 30° nose down the latter time difference (0.8 seconds) is equivalent to an altitude loss of about 300 feet. At 450 knots and 30° nose down, the latter time difference (0.8) is equivalent to an attitude loss of about 300 feet. A continuous function for calculating T_{rr} from ϕ would eliminate the abrupt changes and the resultant early warnings.

b.1.2 Late warnings. No late warnings were associated with the roll recovery calculations.

c. Altitude Loss During Dive Recovery

The algorithm calculates the altitude loss that would occur during a wings level, constant G dive recovery in the following manner:

(1) The basic equation for a constant G constant true airspeed dive

recovery is:

$$\Delta Z_{pu} = \left[\frac{V^2}{g}\right] \ln \left[\frac{n - \cos \gamma_{ext}}{n - 1}\right]$$

Where ΔZ_{pu} = the altitude lost during the pullup

V = aircraft true airspeed (ft/sec)

N = G available (max of 5)

γ_{ext} = extrapolated flight path angle

g = 32.2 ft/sec 2

This equation is based on the assumption that dive recovery is complete when $\gamma = 0°$.

(2) The value for n was determined from a look-up table using the following piecewise linear schedule (Figure 15).

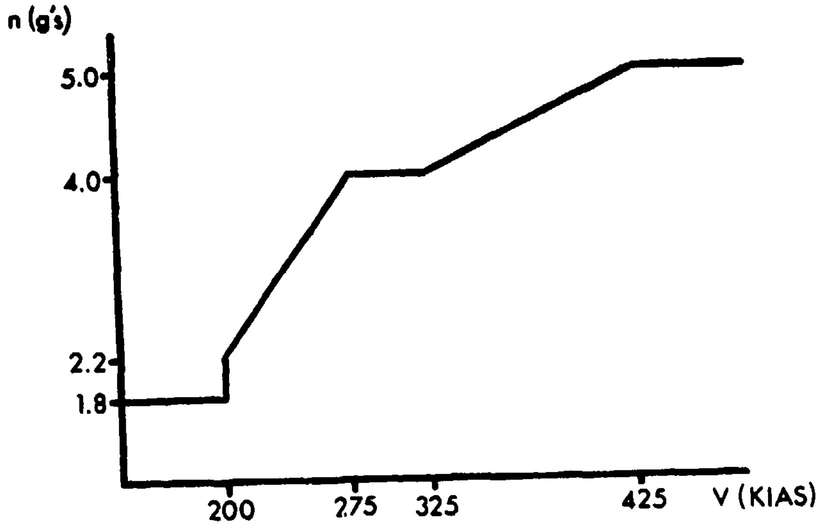


Figure 15 G-Available vs Indicated Airspeed

(3) Since the constant G dive recovery equation does not account for altitude lost during application of G, it was modified, resulting in the

following equation:

$$\Delta Z_{pu} = \left[\frac{K}{n_2}\right] V^2 \ \ln \left[\frac{n_2 - \cos \quad ext}{n_2 - 1}\right]$$

where $\quad N_2 = n$ for $n < 2.2$

$\quad = n/2$ for $n > 2.2$

$K = a_1 V_1 \cos \gamma_{ext} + a_2 \cos \gamma_{ext}$

$\quad + a_3 V_1 + a_4$

$V =$ true airspeed

$V_I =$ indicated airspeed

The constants a_i were derived from data obtained by Cubic during a limited series of controlled dive recoveries in instrumented aircraft. The equation for ΔZ_{pu} was assumed to be of the above form and a curve fit was performed to determine values for constants a_i for five distinct airspeed regimes.

c.1 Problems

c.1.1 Early warnings

c.1.1.1 The equation for ΔZ_{pu}, along with its variables a_i and K, was derived based on the assumption that the pilot will start his dive recovery from a load factor of 1 G. Even during a 5-G dive recovery, the algorithm continues to predict altitude loss based on this equation which (as explained in paragraph c (3) above) has been tailored to include altitude loss during the buildup from 1 to 5 G's. This can cause early warnings under certain conditions. Other times, the warning will stay on after the aircraft is no longer in danger. The designers of the algorithm have compensated for this inflexibility somewhat by reducing the altitude loss due to pilot response time (Paragraph a.) when the aircraft has an upward acceleration, but this does not adequately solve the problem under all conditions.

c.1.1.2 The dive recovery equation calculates altitude loss in reducing γ to zero. In cases where the terrain is rising, this results in an excessive estimate.

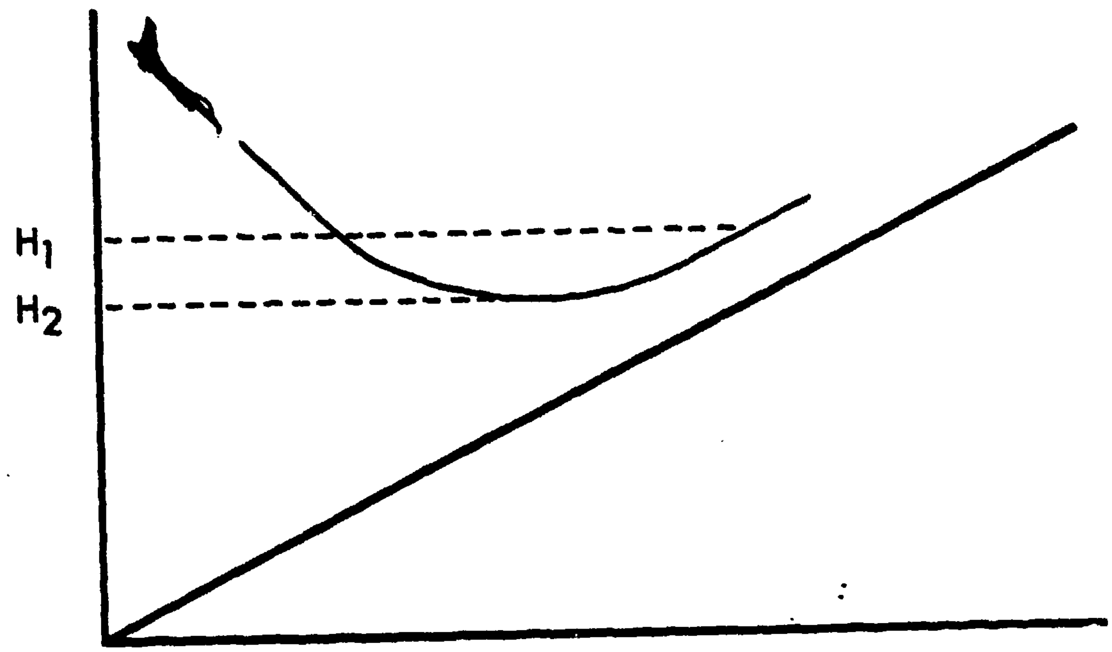


Figure 16. Error Caused by Estimating Δz_{pu} Based on Recovery to $\gamma = 0$

Figure 16 shows an aircraft in a dive recovery in the presence of sloping terrain. The aircraft is nearest the terrain at the point where the flight path angle γ , is equal to the angular slope of the terrain. This altitude H_1, is higher than the altitude where $\gamma = 0$, here represented by H_2. By calculating altitude lost based on reducing γ to zero, an error of magnitude $(H_1 - H_2)$ is introduced, resulting in an early warning.

This is an important consideration in limiting nuisance warnings due to rising terrain. In level flight, approaching rising terrain, calculations based on matching to the terrain slope should result in a negative Δz_{pu}.

c.1.2 Late warnings

No late warnings were noted. However, recommend that the values for K and a_i, if used, be verified through more extensive experimentation.

d. Altitude loss due to terrain rise

The algorithm calculates the altitude loss due to ground rise using a filtered estimation of the terrain slope directly below the air craft. To estimate the change in terrain height during recovery, the slope is extrapolated for a time T_{gr} which is calculated as a function of initial flight path angle. The formula for T_{gr} is:

$$T_{gr} = \left[\frac{2V}{g \quad n^2 + 1}\right] \tan^{-1} \left[\frac{(n^2 + 1) \tan \frac{\gamma}{2}}{n - 1}\right]$$

where:

T_{gr} = time used to calculate ground rise

V = aircraft velocity (ft/sec)

g = 32.2 ft/sec

n = 4 (G's)

γ = aircraft flight path angle

Once T_{gr} has been determined, the following checks are made to determine whether or not to calculate ground rise.

1. Calculate T_{impact}

$$T_{impact} = \frac{\text{Height}}{V_z(\text{terrain}) - V_z(\text{aircraft})}$$

where T_{impact} = the time it will take the aircraft to hit the terrain based on its current vertical velocity ($V_{z(aircraft)}$) and the current rate of ground rise ($V_{z(terrain)}$)

Height = current height above terrain

If $T_{impact} < T_{resp}$, ground rise is not calculated.

(T_{resp} = pilot response time, 2 seconds.)

2. Calculate lower boundary for T_{impact}

$$BOUND_{lwr} = T_{gr} - T_{impact}$$

3. Calculate upper boundary for T impact

$$BOUND_{upr} = T_{gr} + 10 \text{ Seconds}$$

4. If T_{impact} falls between $Bound_{lwr}$ and $Bound_{upr}$, ground rise is calculated:

Ground rise (ΔZ_{gr}) is simply calculated as:

$$\Delta Z_{gr} = (V_{z(terrain)}) \cdot (T_{gr})$$

d.1. Other problems

Assuming that the calculated terrain slope is accurate and the terrain is absolutely consistent, the most accurate way to calculate ground rise is to multiply the slope of the terrain by the horizontal distance the airplane will travel during reaction time, roll recovery, and dive recovery (to match γ to terrain slope). The algorithm calculates terrain rise based exclusively on the time it takes to perform a constant 4-G dive recovery to zero flight path angle. This involves several inaccuracies:

(1) $V_{z(terrain)}$(ft/sec) must be calculated based on the instantaneous

horizontal velocity of the aircraft dx/dt and the slope dh/dx of the local terrain, that is:

$$V_z \text{ (terrain)} = \frac{dh}{dx} \cdot \frac{dx}{dt}$$

Since $\frac{dx}{dt}$ increases during the dive recovery, as the aircraft velocity vector nears horizontal, $V_{z(terrain)}$ should increase. Basing the terrain rise on this initial value of the aircraft's horizontal velocity will result in an underestimation of terrain rise.

(2) The distance traveled during reaction time, roll recovery, and application of recovery G is not considered. The net effect of these omissions is an additional negative error (underestimate) of the terrain rise.

(3) The calculation of T_{gr} is based on reducing γ to zero. Thus, if the airplane is in level flight, approaching rising terrain T_{gr} and ΔZ_{gr} are zero, affording absolutely no protection against rising terrain. If the "dive recovery" portion of the ground rise calculation considered the distance traveled while matching γ to the slope angle of the terrain, more protection would be provided.

(4) From a cursory mathematical analysis of the equation for T_{gr}, it appears that there may be a sign error in the terms $\sqrt{n^2 + 1}$. This equation appears to be based on the following relation for constant - g dive recoveries:

$$\frac{d\gamma}{dt} = \frac{g}{v} \cdot (n - \cos\gamma)$$

$$dt = \frac{v\,d\gamma}{g(n-\cos\gamma)}$$

Integrating both sides of this equation gives:

$$T_{gr} = \int_0^{T_{gr}} dt = \int_0^{\gamma} \frac{V\,d\gamma}{g(n-\cos\gamma)}$$

$$= \frac{2V}{g\sqrt{n^2 - 1}} \tan^{-1}\left[\frac{\sqrt{n^2 - 1}\tan\frac{\gamma}{2}}{n - 1}\right]$$

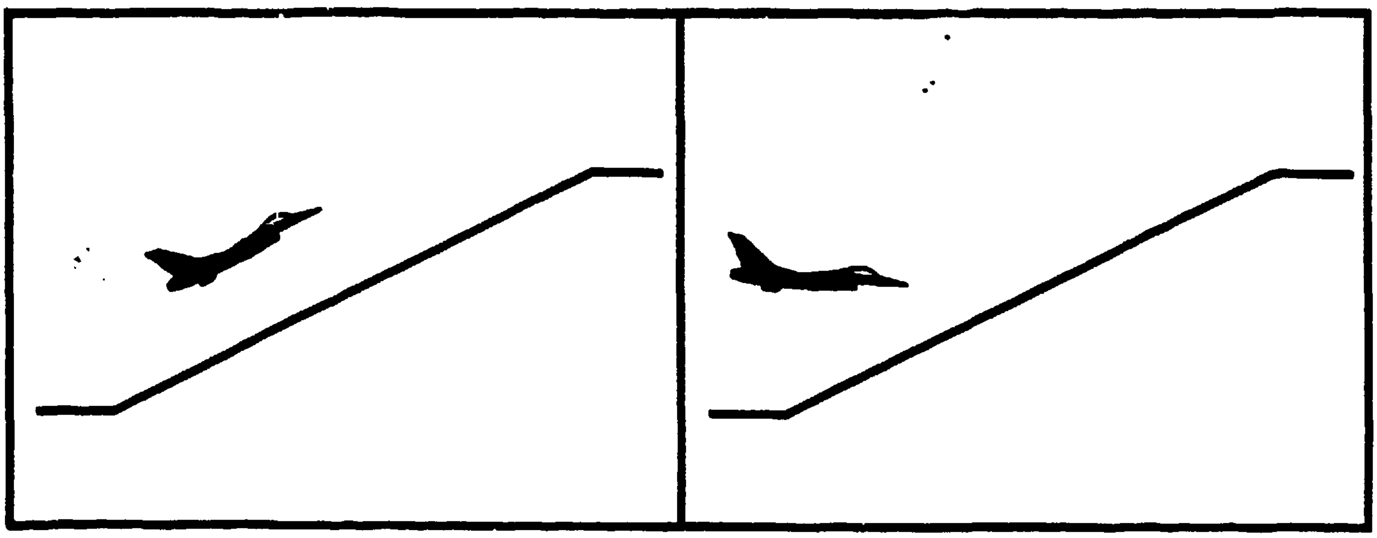
(Ref: CRC Standard Mathematical Tables, Fifteenth Edition, Integral No.260)
Note the terms $\sqrt{n^2 - 1}$ in place of $\sqrt{n^2 + 1}$.

This introduces an error as does the use of 4G's instead of 5G's (or G available) for the quantity n.

(5) Since the algorithm takes the absolute value of the quantity

$$\tan^{-1}\left[\frac{\sqrt{n^2+1}\ \tan\frac{\gamma}{2}}{n-1}\right]$$

a positive value will be returned for T_{gr} whether the aircraft is climbing or diving. Thus, an airplane in a slight climb, well clear of rising terrain will receive a nuisance warning, where an aircraft in level flight, in danger of striking that same terrain will receive no warning at all (Figure 17).

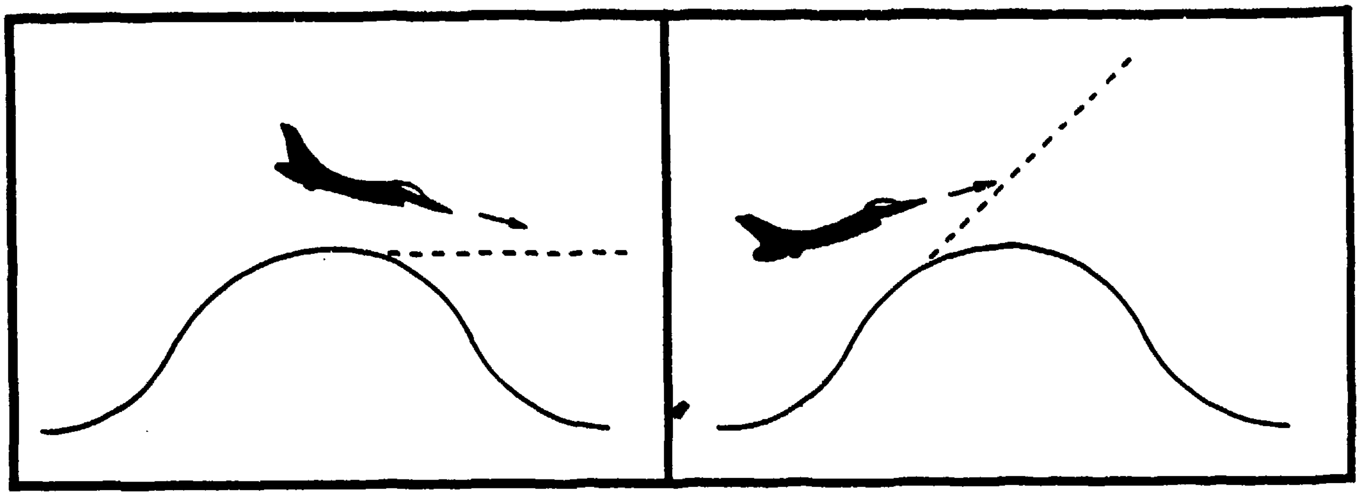


(a)
This aircraft receives a nuisance warning.

(b)
This aircraft receives no warning at all.

Figure 17

(6) Since the algorithm uses a linear function to project the change in terrain elevation, early warnings occur whenever the first deviative of the terrain slope is negative (Figure 18). Basically, the linear predictor is too steep for upslopes and too shallow for downslopes.



(a)
Too shallow for downslope

(b)
Too steep for upslope

Figure 18

Because of previously discussed characteristics of the GCAS algorithm, very few warnings occurred as the aircraft approached rising terrain. However, when a "bunting" maneuver was performed (a slight negative-G pushover) to descend on the back side of a ridgeline, numerous false warnings were experienced. It is possible that some of the false warnings could be eliminated if a modified second order curve were used to predict terrain elevation.

LATE WARNINGS

RISING TERRAIN, LONG STEEP TURN

- CARA BEYOND LIMITS
- AIRCRAFT DOES NOT "SEE" RISING TERRAIN

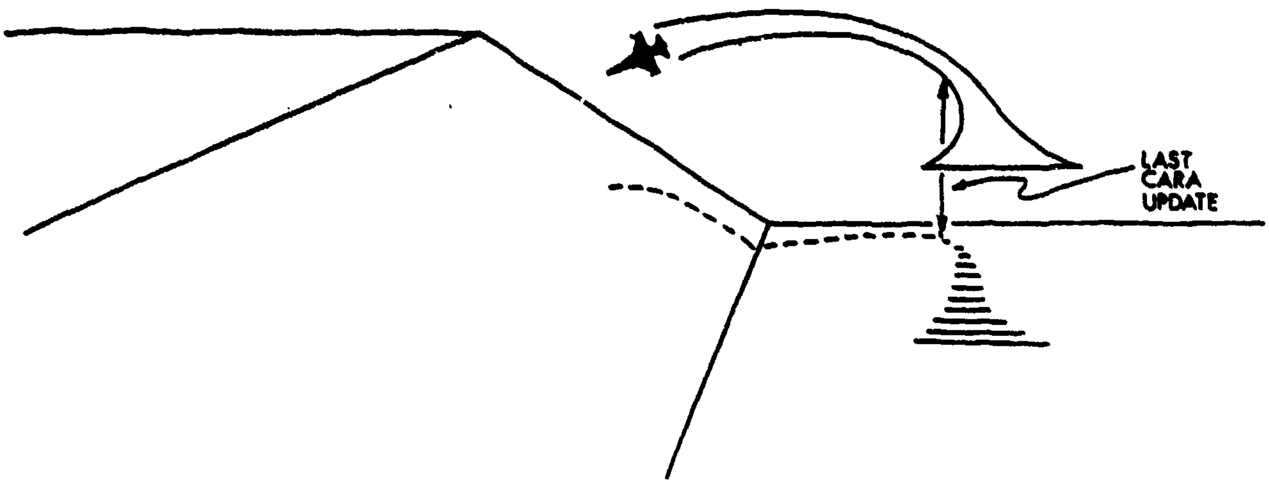


Figure 19 Late Warnings -- Terrain Extrapolation

INVALID WARNINGS OCCUR IN LONG, DESCENDING TURNS

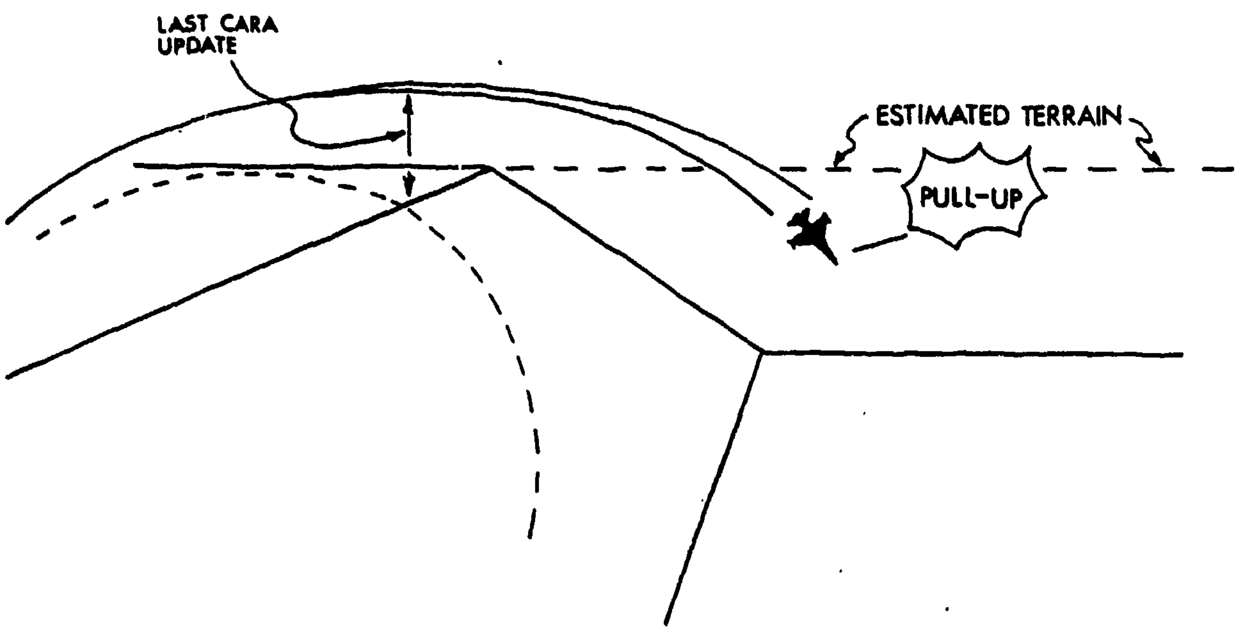


Figure 20 Nuisance Warnings -- Terrain Extrapolation

4. TERRAIN ESTIMATION

The GCAS algorithm is designed for use in conjunction with the Combined Altitude RADAR Altimeter (CARA), which is specified to provide accurate altitude whenever the aircraft bank and pitch angles are less than $\pm 60°$ and $\pm 45°$ respectively. No forward looking sensor is available to measure terrain height along the predicted flight path. A Kalman Filter provides an estimate of terrain elevation and terrain slope beneath the aircraft. When the CARA inputs are unavailable, the algorithm retains the last estimated terrain altitude and extrapolates it according to its last estimated slope for a period of time, T_{ext}, which varies according to aircraft flight parameters and terrain consistency. When this time period has expired, the extrapolation is discontinued and the last terrain height estimate is held until CARA inputs are restored.

This approach allows the GCAS to continue to provide protection over a much larger range of flight maneuvers than most alternative systems, which merely shut down when a current sensor input is unavailable. However, some problems were encountered during the simulation which demonstrated limitations to the effectiveness of the terrain extrapolation/hold feature.

The basis for all the limitations is the fact that terrain is, to a large degree, unpredictable. If, as in Figure 19, for instance, the air craft is in a long, high-banked (>60°) turn, and encounters abruptly rising terrain, no warning will be provided. If the aircraft is in a descending turn over an abrupt drop off, such as a ridge (Figure 20), an invalid warning will occur as the aircraft approaches the estimated terrain altitude. These faults are more or less unavoidable as long as a bank limited sensor with no forward-looking capability is used. Overall, it appears that in spite of the shortcomings, the terrain hold/extrapolation feature is a worthwhile addition to the GCAS. In comparision to systems with no extrapolation feature, GCAS:

1. Provides increased protection during large amplitude maneuvering over flat or regularly sloping terrain.
2. Increases the number of nuisance warnings slightly due to turning descents over irregular terrain.
3. Provides the same proteccion against steep turns into rising terrain--none.

5. RECOMMENDATIONS

There is no question that Cubic's approach to the GCAS process is most ambitious and promising. The concept of terrain estimation, both for periods when the sensor inputs are degraded and for prediction of altered loss due to upslope, may give GCAS a capability unmatched by any system using similarly limited sensors.

Recommend, however, that the preceding analysis be considered carefully prior to implementation of the system. Follow-on testing in actual aircraft should be used to evaluate the Kalman Filter and its capability with a CARA system over actual terrain. These portions of the system could not be properly evaluated in the simulator due to (1) dissimilarities between simulator terrain data base and actual terrain and (2) uncertainties about the true characteristics of CARA. If the limitations mentioned herein are adequately remedied, then the generic GCAS stands a very good chance of saving valuable aircraft and irreplaceable crews.

6. RESULTS

In order to integrate the pilot performance/response time data with the GCAS algorithm analysis and pilot questionnaire, a brief summary is appropriate. First, the duration of the GCAS warning varied depending on type of mission flown. The GCAS duration ranged from 1.85 seconds for low level navigation to 4.38 seconds for IMC unusual attitudes. The average warning duration across all missions was 3.1 seconds (S.D. = 2.34). As is the case with most response time data, it tends to be slightly skewed due to a variety of factors that were discussed.

The average response time to a GCAS warning is 0.66 seconds with a standard deviation of 0.30. Taking all factors discussed into account and adding 2 sigma to the mean response time, the recommended allowance for pilot response in the GCAS is 2 seconds. Performance data were also gathered in time to maximum G (M = 2.68; S.D. = 1.39), maximum G's pulled (M = 4.62; S.D. = 2.34), and time to zero flight path angle (M = 3.88; S.D. = 2.56).

The Algorithm Analysis indicates some modifications are necessary including the following:

1) Modifications for smoothing roll, roll rate and acceleration.
2) Shortening flight path extrapolation for negative G "bunts."
3) Adjusting roll recovery rates and varying them with airspeed and bank.
4) Modifying method of computing terrain rise.
5) Modifying reaction time allowance at zero flight path angle.

Finally, the questionnaire data indicated a good pilot acceptance and the results indicate that GCAS is a viable system for partial solution of CFIT.

SECTION IV

CONCLUSIONS

1. A generic GCAS appears to be a useful system that has good pilot acceptance, but needs some improvements prior to implementation.

2. The recommended improvement to the algorithm should be incorporated and verified in simulation (see recommendations).

3. Flight test the improved system.

GROUND COLLISION AVOIDANCE SYSTEM PILOT QUESTIONNAIRE

INSTRUCTIONS: The purpose of this questionnaire is to obtain information from you about your previous flying experience. Your answers to these questions will help us in our evaluation of this simulation. Your honest opinions are, therefore, essential and will be kept confidential.

If you have any questions, please ask the questionnaire administrator for assistance. Take as much time as necessary to answer the questionnaire.

PERSONAL DATA:

Name (last, first, mi): ______________________________

Rank: ______________________________

Duty AFSC: ______________________________

Organization and Symbol: ______________________________

Duty Station: ______________________________

Duty Phone: ______________________________

Wing Commander, Squadron Commander, DO: ______________________________

Aero Rating: ______________________________

Age: ______________________________

Height: ______________________________

Weight: ______________________________

Vision, Corrected: ______________ Uncorrected: ______________

Years in Military Service: ______________________________

What type(s) of aircraft have you flown? (List)

Aircraft: ______________________________

Fighter hours: ______________________________

F-16 Hours: ______________________________

Hours Flying with Radar Altimeter: ______________________________

Total Flight Time (Include Student Hours): ______________________________

PILOT QUESTIONNAIRE

1. Do you feel the "pull-up" warning alarms were initiated for the most part:

    1. Too early
    2. Slightly early
    3. Just Right
    4. Slightly late
    5. Too late

2. Did the warning system get your attention?

    1. Yes, all the time
    2. Yes, most of the time
    3. Occasionally
    4. Seldom
    5. Never

3. How often did you get nuisance warnings?

    1. All the time
    2. Most of the time
    3. Occasionally
    4. Seldom
    5. Never

4. Were there any instances, in your opinion, where the system provided no warning when it should have? Describe the circumstances.

____

____

____

5. What do you feel is the usefulness of a GCAS system?

    1. Extremely useful
    2. Useful
    3. Moderate usefulness
    4. Useless
    5. Extremely useless

6. How often, if ever, would you tend to over rely on a GCAS warning system (i.e., using the system as a pull-up cue during a bombing mission)?

   1. All the time
   2. Frequently
   3. Occasionally
   4. Seldom
   5. Never

7. How would you rate the adequacy and suitability of the GCAS warning?

   1. Excellent, optimum warning system
   2. Very good
   3. Good
   4. Satisfactory, but improvements could be made
   5. Satisfactory, but improvements are essential
   6. Poor
   7. Very Poor

8. Were there any design considerations omitted that you consider essential to GCAS?

9. General comments on GCAS

10. Comment on the adequacy of this simulation for rating a Ground Collision avoidance system algorithm.

QUESTIONNAIRE DATA

Q. (1.) Were there any instances, in your opinion, where the system provided no warning when it should have? Describe the circumstances.

Pilot No. 1: Yes, on the low level mission (No. 11), I skimmed the ground with no warning at the very beginning.

Pilot No. 2: No.

Pilot No. 3: No.

Pilot No. 4: No.

Pilot No. 5: No.

Pilot No. 6: No.

Pilot No. 7: No.

Pilot No. 8: No.

Pilot No. 9: When flying into rising terrain (but it's not meant to provide that protection). It also seemed slow to react to a level bunt into flat terrain.

Q. (2.). Were there any design considerations omitted that you consider essential to GCAS?

Pilot No. 1: No.

Pilot No. 2: Only one, maybe looking out in front of the jet some would help, if possible.

Pilot No. 3: None.

Pilot No. 4: One improvement discussed would provide an optical vernier representation of an approaching pull-up call (i.e., how close am I to getting a pull-up call).

Pilot No. 5: Pilot warning as to need to pull-up prior to it being critical to pull.

Pilot No. 6: More timely voice.

Pilot No. 7: Wider looking radar Altimeter. Predictive curvature at ranges for ridge crossings (i.e., when inverted ridge crossing needs to predict curve).

Pilot No. 8: Yes, there should be a method, such as foward radar altimeter, to include terrain in front in the algorithm.

This would eliminate most, if not all, nuisance warnings.

Pilot No. 9: A clear signal distraction when GCAS comes on in the AUTO mode. Brief glitches leave you wondering what happened.

Q. (3.) General comments on GCAS.

Pilot No. 1: System works well as long as no trim inputs caused. Need to correct ridge crossings so pilot doesn't get too many nuisance warnings during ridge crossings.

Pilot No. 2: Seemed to work quite well. Only problem was with nuisance warnings after ridge crossings.

Pilot No. 3: A good system, needs further testing/changes for false warnings after ridge crossings. Also, false warnings when flying alongside a ridge. It appeared that the radar altimeter was looking sideways.

Pilot No. 4: Good system. Due to less than optimum VIS, the system appeared to have good potential. If the pilot can turn the system on/off, it would be great in some circumstances. That is, missions flown into the sun in the desert where hills blend into the shadows, etc.. Ridge crossings seem to trip the system too much.

Pilot No. 5: Manual system worked pretty well as a heads up call to a distracted pilot; even though the system had problems on the downhill side of a ridge crossing (false warning).

Pilot No. 6: Needs work on ridge crossings.

Pilot No. 7: Good concept. Eliminate false warnings and will be helpful.

Pilot No. 8: GCAS is essential. I think this system is a good start. I think you could put this present algorithm in the F-16 today and it would be adaquate, although pilots would be apt to complain about the nuisance calls. I theorize pilots might actually fly their aircraft differently so as to minimize nuisance warnings. The only way to eliminate these false warnings is to have a foward-looking source as well as the standard radar altimeter. One other comment: the two second reaction time may be too long in the algorithm. It was hard to simulate this since I was expecting many of the warnings but in the aircraft, I think a pilot might react slightly quicker than two seconds to an unexpected warning (pull-up now, ask questions later). Over all, it's a good system!

Pilot No. 9: Needs to be given without delay. The false warnings on ridges were less frequent than I expected so the warnings that did come on, occasionally took me by surprise.

Q. (4.) Comment on the adequacy of this simulation for rating a Ground Collision Avoidance System algorithm.

Pilot No. 1: Will cut down on CFIT, but I don't think the system will completely eliminate the ground collision problem.

Pilot No. 2: Very good. Naturally, since you can't have perfect visual simulation you can't duplicate conditions perfectly, but it seemed to work fairly well.

Pilot No. 3: None.

Pilot No. 4: Good. The lack of periferal vision makes turning at low altitude and performing additional tasks tough.

Pilot No. 5: Very good. The simulator flies much like the jet.

Pilot No. 6: Good.

Pilot No. 7: Good.

Pilot No. 8: Fairly poor. Biggest problems: visual perceptions of depth, lateral position, and poor lighting. It is quite possible that one may have almost no nuisance warnings if the aircraft was flown (over).

Pilot No. 9: The profile was great.

Q. (5.) How does the "slope" warning compare to the pull-up call?

Pilot No. 1: Good for level terrain, but useless with really steep ridges.

Pilot No. 2: I like it well enough, but at low altitude it could give you a warm feeling falsely when you in fact should be getting a "Pull-up." Could be very useful for insidiously rising terrain.

Pilot No. 3: Pull-up is all that is necessary.

Pilot No. 4: I like "UPSLOPE." It is less harsh, a remark rather than a command.

Pilot No. 5: The slope call seemed kind of useless in that it came on about one second before the pull-up command. The upslope should either occur much earlier or not at all. (That is to say, only have the pull-up command.)

Pilot No. 6: Use pull up all the time.

Pilot No. 7: No value. Either call brings your attention inside and evaluate the situation(i.e., you are not going to start and pull unless you know your attitude).

Pilot No. 8: Not necessary. It defines too narrow a range of conditions, and almost overlaps the already adequate pull-up call. Besides, pilot reaction would be the same, so why use two warnings?

Pilot No. 9: I did not see much utility in the slope. The actions were the same, so I would stay with one.

TEST PROCEDURE

	MON	TUE	WED	THU	FRI
WEEK 1 A.M.				2 TEST MISSIONS	2 TEST MISSIONS
P.M.			IN-BRIEF AND TRAIN (PILOTS 1 AND 2)	2 TEST MISSIONS	2 TEST MISSIONS AND DEBRIEF
WEEK 2 A.M.	IN-BRIEF AND TRAIN (PILOTS 3 AND 4)	2 TEST MISSIONS	2 TEST MISSIONS AND DEBRIEF	2 TEST MISSIONS	2 TEST MISSIONS
P.M.	2 TEST MISSIONS	2 TEST MISSIONS	IN-BRIEF AND TRAIN (PILOTS 5 AND 6)	2 TEST MISSIONS	2 TEST MISSIONS AND DEBRIEF
WEEK 3 A.M.	IN-BRIEF AND TRAIN (PILOTS 7 AND 8)	2 TEST MISSIONS	2 TEST MISSIONS AND DEBRIEF	2 TEST MISSIONS	2 TEST MISSIONS
P.M.	2 TEST MISSIONS	2 TEST MISSIONS	IN-BRIEF AND TRAIN (PILOTS 9 AND 10)	2 TEST MISSIONS	2 TEST MISSIONS

MISSION BRIEFINGS

MISSION 11 - LOW LEVEL NAVIGATION

OBJECTIVE: Evaluate GCAS algorithm for nuisance warnings/pull-ups during aggressive low-level maneuvering.

SCENARIO: This is a low-level nav mission planned at 300 to 500 feet, 480 knots. Fly the nav profile as closely to the planned line as possible. Threats are active above 800 AGL. Fly as aggressively as you can to stay below 500 feet. You have programmed TOS's for each steerpoint.

START:

Altitude:	2200 MSL
Groundspeed:	480 Knots
Heading:	210

INSTRUCTIONS:

1. Make your TOS (Groundspeed cue will help).
2. Stay below 800' or get zapped!
3. Evaluate each "pull-up" call as:

   A. Valid
   B. Invalid, expected
   C. Invalid, unexpected

MISSION 12 - LOW SPEED MANEUVERING, IMC

OBJECTIVE: Evaluate GCAS low speed effectiveness against varied terrain.

SCENARIO: You have just completed an enroute descent to Buzzard Creek AFB. Since you lost the approach plate, you have asked for radar vectors to a PAR final. The controller has assigned you an altitude of 1800 feet MSL. That sounds pretty low, but you think you remember that the MSA was 1400 feet. You are in IMC. Your radar altimeter is busted.

START:
Altitude: 1800 feet MSL
Airspeed: 250 KCAS
Heading: 268 degrees

INSTRUCTIONS:

1. Maintain 250 KCAS and follow the steerpoint cues.
2. If you get a pull-up alert, pull as hard as you can--use power as you feel the situation dictates.
3. Climb to 3000 MSL for 15 seconds, then descend expeditiously to 1800 feet again.

MISSION 13 - HARD TURNS AT LOW ALTITUDE

OBJECTIVE. Evaluate GCAS effectiveness during hard defensive maneuvering at low altitude.

SCENARIO: You are practicing hard defensive turns at low altitude. You will fly a figure 8 pattern between Millersburg and Elizabethville. To keep you honest, a "SAM" threat will sound each time you go above 800 AGL.

START: 1000 feet MSL (500 AGL)
Heading: 094
Airspeed: 480

INSTRUCTIONS:

1. At each steerpoint, make a hard (5-G) turn back toward the next steerpoint.
2. Always turn toward the north, away from the mountains.
3. Each time you turn, you will be instructed to read a series of numbers and letters from a card located above your head to simulate checking 6. Try to maintain your G-load and altitude while you read the data.
4. If you get a warning, recover and continue.

MISSION 14 - RANGE MISSION

OBJECTIVE: Evaluate GCAS effectiveness during a complex range mission with side tasking.

SCENARIO: This is your first trip to the Berrysburg Bombing Range. You are trying out a number of alternate run-ins for straight ahead pop-up deliveries. Because of a peculiar local airspace restriction, you must remain at or below 500 AGL except in the target area.

START:

Altitude:	1300 feet MSL
Airspeed:	480 knots
Heading:	199
Weapons:	4 MK 82's, stns 3 7, CCIP/Singles RP - 1

INSTRUCTIONS:

1. Make 4 straight ahead pop-up attacks on the Berrysburg target.
2. The sequence of the runs is on your map. After each run, fly to the bend in the river and then along Hooflander Mountain.
3. If you are in doubt, follow the steerpoints. Console operator will help.
4. Make tight turns (at least 3 G's).
5. Start your pull-up when you are 20 seconds from target.
   - pull up 30 degrees.
   - pull down at 4000 feet MSL (30 degrees).
   - release at 2500 feet MSL.
   - do your best not to short the pass -- even if you feel a bit steep (unless you get a pull-up warning).
6. Stay in the NAV Master Mode until you are on run-in heading, then select A/G.
7. You will be asked to perform additional tasks during the mission.
8. If you get a pull-up warning, recover and continue the mission.

MISSION 15 - LOW LEVEL NAV/POP-UP DELIVERIES

OBJECTIVE: Evaluate the GCAS effectiveness during low altitude tactical navigation/weapons delivery.

SCENARIO: This is a combined nav/weapons delivery profile. There are three targets planned for straight ahead pop-up deliveries. The targets are fairly easy to see: a bridge, a ship, and an airfield. The area is heavily defended. If you climb above 800 feet AGL, you will get a "SAM" warning.

START:
Altitude: 2100 feet MSL (500 feet AGL)
Airspeed: 480 knots
Heading: 054
Weapons: 6 Mk 82's/Pairs/RP 1/CCIP

INSTRUCTIONS:

1. Fly 480 knots G's or the speed required to make your TOT. Turns are 60 degrees bank. Stay at 300 AGL except during weapons delivery. Maintain 480 feet during target run on.
2. Weapons Delivery:

TGT	Pull-Up	Pull-Down	Release
1 (Bridge)	30 degrees at 20 sec	4100 feet	2600 feet
2 (Ship)	30 degrees at 20 sec	4000 feet	2500 feet
3 (Airport)	30 degrees at 20 sec	4000 feet	2500 feet

3. If you get a pull-up warning, recover and continue the mission at the planned altitude.
4. If you get a warning during NAV leg, evaluate it as either:

   A. Valid
   B. Invalid, expected
   C. Invalid, unexpected

MISSION 16 - IMC MANEUVERING

OBJECTIVE: Evaluate the system's effectiveness in recovering from situations where spatial disorientation is a factor.

SCENARIO: You will perform a number of aerobatic maneuvers in IMC.

NOTE: A non-standard HUD Bank display will be used to help your attitude awareness.

INSTRUCTIONS:

1. Stay within 10 nmi of steerpoint "1". Try to work back and forth between STPT 1 and 2.
2. Perform the following maneuvers:

	A/S	ALT (feet)	G's	POWER
Split S	300	8000	G's and power as required to maintain 300 knots.	
Loop	500	3000	5	MIL
Cuban 8	500	3000	5	MIL
Sliceback	350	8000	3-5	MIL
Double Split S	300	14000	G's and power as required to maintain 300 knots.	

3. If you get a pull-up warning, complete the recovery to a safe altitude above 5000 feet and set up for the next maneuver.

REFERENCES

1. Linquist, E.F., Design and Analysis of Experiments in Psychology and in Education. Boston: Houghton Mifflin Co., 1953.

2. ASD/AG, Draft Statement of Work, 14 March 1986.

3. Cubic Corporation, Feasibility Demonstration of a Ground Collision Avoidance System, Technical Report 414-1A, 1 September 1985.